

This is a repository copy of *Inhibiting translation elongation can aid genome duplication in Escherichia coli*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/109285/>

Version: Accepted Version

---

**Article:**

Myka, Kamila Katarzyna, Hawkins, Michelle [orcid.org/0000-0001-9393-8206](https://orcid.org/0000-0001-9393-8206), Syeda, Aisha H [orcid.org/0000-0003-3201-4135](https://orcid.org/0000-0003-3201-4135) et al. (6 more authors) (2017) Inhibiting translation elongation can aid genome duplication in *Escherichia coli*. *Nucleic Acids Research*. pp. 2571-2584. ISSN 0305-1048

<https://doi.org/10.1093/nar/gkw1254>

---

**Reuse**

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial (CC BY-NC) licence. This licence allows you to remix, tweak, and build upon this work non-commercially, and any new works must also acknowledge the authors and be non-commercial. You don't have to license any derivative works on the same terms. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

## **Inhibiting translation elongation can aid genome duplication in *Escherichia coli***

Kamila K. Myka<sup>1,6</sup>, Michelle Hawkins<sup>1</sup>, Aisha H. Syeda<sup>1</sup>, Milind K. Gupta<sup>2</sup>, Caroline Meharg<sup>3</sup>, Mark S. Dillingham<sup>4</sup>, Nigel J. Savery<sup>4</sup>, Robert G. Lloyd<sup>5</sup>, Peter McGlynn<sup>1,7</sup>

<sup>1</sup>Department of Biology  
University of York  
Wentworth Way  
York  
YO10 5DD  
UK

<sup>2</sup>School of Medical Sciences  
Institute of Medical Sciences  
University of Aberdeen  
Aberdeen AB25 2ZD  
UK

<sup>3</sup>Institute for Global Food Security  
Queen's University Belfast  
David Keir Building  
Malone Road  
Belfast  
BT9 5BN  
UK

<sup>4</sup>DNA-Protein Interactions Unit  
School of Biochemistry  
University of Bristol  
Bristol BS8 1TD  
UK

<sup>5</sup>Centre for Genetics and Genomics  
University of Nottingham  
Queen's Medical Centre  
Nottingham NG7 2UH  
UK

<sup>6</sup>Present address:  
Department of Microbiology and Immunology  
Columbia University Medical Center  
New York NY 10032  
USA

<sup>7</sup>Corresponding author  
e-mail: peter.mcglynn@york.ac.uk  
Telephone: +44 (0)1904 328688  
FAX: +44 (0)1904 328505

The authors wish it to be known that, in their opinion, the first two authors should be regarded as joint First Authors.

**Running title:** Replication, transcription and translation elongation.

**Keywords:** genome stability/DNA repair/replisome/antibiotic/stringent response

## Abstract

Conflicts between replication and transcription challenge chromosome duplication. *Escherichia coli* replisome movement along transcribed DNA is promoted by Rep and UvrD accessory helicases with  $\Delta rep \Delta uvrD$  cells being inviable under rapid growth conditions. We have discovered that mutations in a tRNA gene, *aspT*, in an aminoacyl tRNA synthetase, AspRS, and in a translation factor needed for efficient proline-proline bond formation, EF-P, suppress  $\Delta rep \Delta uvrD$  lethality. Thus replication-transcription conflicts can be alleviated by the partial sacrifice of a mechanism that reduces replicative barriers, namely translating ribosomes that reduce RNA polymerase backtracking. Suppression depends on RelA-directed synthesis of (p)ppGpp, a signalling molecule that reduces replication-transcription conflicts, with RelA activation requiring ribosomal pausing. Levels of (p)ppGpp in these suppressors also correlate inversely with the need for Rho activity, an RNA translocase that can bind to emerging transcripts and displace transcription complexes. These data illustrate the fine balance between different mechanisms in facilitating gene expression and genome duplication and demonstrate that accessory helicases are a major determinant of this balance. This balance is also critical for other aspects of bacterial survival: the mutations identified here increase persistence indicating that similar mutations could arise in naturally occurring bacterial populations facing antibiotic challenge.

## Introduction

Cell survival from one generation to the next relies on efficient and faithful replication of the genome. However, the template for replication frequently harbors obstacles that have the potential to interfere with the progression of replisome complexes, the macromolecular machines responsible for driving genome duplication. Protein-DNA complexes are important sources of such obstacles and those associated with transcription are especially problematic, in part because of their abundance and in part because they present multiple different challenges to replisome movement (1-4). One major challenge is the very high free energy of binding of transcription complexes that creates a need to disrupt many RNA polymerase-nucleic acid interactions as replication proceeds. Transcribing RNA polymerases (RNAPs) also pause frequently either spontaneously or upon encountering DNA template damage (5). Paused RNAPs can also diffuse backwards along the template resulting in displacement of the transcript 3' end from the RNAP active site. This causes an inability to resume transcription, creating barriers to replication that threaten genome stability (6,7).

Mechanisms exist that reduce the probability of a replication fork encountering paused transcription complexes. Upstream RNAPs on the DNA and ribosomes on the emerging transcript may inhibit backtracking of a paused transcription complex in bacteria (7-9). RNA translocases such as the bacterial Rho hexamer can also translocate along transcripts not coated with ribosomes and displace paused and blocked RNAPs (7,10,11). Rho translocation also disrupts R-loops, structures in which an RNA transcript hybridises to the DNA template strand (11). Nucleases can also aid genome duplication by promoting the resumption of transcription by backtracked RNAP (7,12). GreA and GreB bind to *E. coli* RNAP and stimulate cleavage of backtracked transcripts, creating a new RNA 3' end that can be used to restart transcription (13). Conversely, the 3'-5' helicase UvrD can increase rather than decrease backtracking of RNAP and this may increase access of nucleotide excision repair enzymes UvrABC to DNA damage thus helping to clear barriers to RNAP and aid genome duplication (14).

Signalling molecules such as guanosine tetraphosphate and pentaphosphate in bacteria (referred to collectively as (p)ppGpp) can also reprogramme transcription. (p)ppGpp is central to the stringent response in bacteria, identified originally as a response to amino acid starvation in which the presence of uncharged tRNA within the ribosomal A site stimulates ribosome-bound RelA to synthesise (p)ppGpp (15-17). Control of the stringent response also requires a (p)ppGpp-specific pyrophosphohydrolase, SpoT, that also has low (p)ppGpp synthase activity (17). However, the synthase activity of SpoT is induced by other stresses such as depletion of fatty acids (18). Central to the stringent response is binding of (p)ppGpp to RNAP which leads to downregulation of stable RNA production and upregulation of stress response genes (17,19,20). Expression of ribosomal rRNA operons accounts for half of all transcription during rapid growth when (p)ppGpp levels are low and thus provides the majority of transcriptional obstacles to replisomes *in vivo* when cells are dividing quickly (21-24). Elevated (p)ppGpp therefore reduces conflicts between replication and transcription by decreasing the density of transcribing RNAPs on the genome. (p)ppGpp can also decrease the stability of transcription complexes blocked by template damage *in vitro* which may decrease the density of blocked RNAP on the genome (12). This destabilisation has been questioned, though, and a role for (p)ppGpp in increasing the fidelity of transcription and hence reducing RNAP pausing and backtracking has been proposed (25). Other work implicates (p)ppGpp acting synergistically with UvrD in promoting backtracking of paused RNAP, one function of which could be to facilitate transcription-coupled repair of any pause-inducing DNA damage (26). Thus how (p)ppGpp might act on transcription elongation complexes, as opposed to transcription initiation, is still far from clear. Transcription is not the only target of



(p)ppGpp, though, since (p)ppGpp also binds multiple other targets. Inhibited targets include DnaG primase (27-30) and the translation elongation factors EFG and EF-Tu (31), indicating the pleiotropic impact of elevated (p)ppGpp on replication, transcription and elongation. (p)ppGpp also affects other diverse aspects of metabolism such as phospholipid synthesis, oxidative metabolism and resistance to antibiotics (32). These signalling molecules also enhance the ability of *E. coli* to persist in the presence of antibiotics. Persistence is the non-heritable ability of a small fraction of a bacterial population to survive exposure to an otherwise lethal concentration of antibiotic (33). (p)ppGpp levels vary stochastically in a bacterial population and increased (p)ppGpp activates toxin-antitoxin systems that induce slow growth in a sub-population of cells, leading to antibiotic tolerance (34).

Mechanisms also exist to increase the probability of continued replisome movement in the event of a collision with an RNAP. Accessory replicative motors provide a supply of additional helicases at the fork to aid protein displacement ahead of the replisome (35,36). In *E. coli* Rep helicase promotes movement of replisomes along protein-bound DNA *in vitro* and *in vivo* (22,37). Rep appears to be the main replisome anti-pausing factor in *E. coli* (38) and absence of Rep results in at least a two-fold increase in genome duplication time (39,40) and higher dependence on recombination-directed repair of damaged forks (41-44). However,  $\Delta rep$  cells remain viable since the homologous helicase UvrD can substitute for the absence of Rep at the replication fork (22,37). This substitution is only partial, though, and correlates with a physical and functional interaction between DnaB and Rep but not between DnaB and UvrD (37,45). This partial functional overlap is sufficient for single deletion mutants to be viable during rapid growth whereas  $\Delta rep \Delta uvrD$  cells are not (46).  $\Delta rep \Delta uvrD$  inviability can be suppressed by growth on minimal medium, conditions under which (p)ppGpp levels are high, and also by elevation of (p)ppGpp levels on rich medium via the *spoT1* mutation encoding a (p)ppGpp pyrophosphorylase-defective SpoT (22,37). Mutations within *rpo* genes can also suppress  $\Delta rep \Delta uvrD$  rich medium lethality (22,37,47). These mutant RNAPs display different phenotypes suggesting distinct mechanisms of suppression but some seem to phenocopy elevated (p)ppGpp and/or reduce RNAP backtracking (12,47,48).

The above mechanisms reduce conflicts between replication and transcription but under rapid growth conditions forks are still blocked sufficiently frequently to require replisome reloading enzymes to maintain viability (49,50). Replisome reloading also often requires remodelling of the DNA at the blocked fork by recombination enzymes in order to generate a DNA structure suitable for replisome reloading (51). However, recombinational processing can lead to genome instability and is thus tightly controlled. One control is exerted by UvrD as it can disrupt RecA-ssDNA filaments and this disruption prevents excessive RecFOR-dependent loading of RecA onto ssDNA at blocked forks (52). Such excessive RecA loading contributes to  $\Delta rep \Delta uvrD$  lethality, evinced by the weak suppression of  $\Delta rep \Delta uvrD$  rich medium lethality via mutations in *recF*, *recO* or *recR* (37,53,54).

We have searched for suppressors of  $\Delta rep \Delta uvrD$  rich medium lethality that are not within *rpo*, *spoT*, *recF*, *O* or *R*. We identified a spontaneous suppressor in a tRNA gene, *aspT[t8c]*, that mutated a highly conserved residue that is structurally important in other tRNA species. Probing the basis of this suppression revealed that defective tRNA aminoacylation or inefficient peptide bond formation within the ribosome also suppressed  $\Delta rep \Delta uvrD$  lethality. In all cases suppression required RelA-directed (p)ppGpp synthesis indicating that stalling of ribosome translocation by uncharged tRNA in the A site of ribosomes underpinned suppression. Thus although efficient translation elongation aids genome duplication (7,9), the partial inhibition of ribosome translocation is more effective at mitigating replication-transcription conflicts. These data illustrate the fine balance between the multiple mechanisms that promote simultaneous gene expression and genome duplication

and reveal the importance of accessory replicative helicase activity in determining this balance.

## Materials and Methods

### Plasmids and strains

pAM403 (55) and pAM407 (37) are pRC7 derivatives encoding *rep* and *uvrD*, respectively. p3LC-TL30-5P and p3LC-TL30-5D contain a *cadC-lacZ* gene fusion in which five tandem codons present within the linker encode proline or aspartate, respectively (56). Strains were constructed by P1 *vir* transduction and are listed in Supplementary Table 1.

### Genome sequencing and analysis

DNA was extracted from 1 culture each of strain N7153 and N7182 grown in LB broth to stationary phase using Qiagen 100/G genomic tips from 5 ml cultures following the manufacturer's protocol. Genome sequencing was performed using an Illumina GAIIX instrument with 100 bp paired end reads. Paired reads were trimmed to remove adapters and mapped against the *E.coli* K12 strain MG1655 NC\_000913 genome using bwa (57), duplicates marked using Picard (<http://broadinstitute.github.io/picard>) and variant analysis performed with SAMtools (58), followed by merging of variant tables using perl. Identified high quality synonymous and non-synonymous single nucleotide polymorphisms were annotated manually using the Integrative Genomics Viewer (59). The Illumina data were submitted in form of fastq files to the European Nucleotide Archive (ENA) and are available under accession number PRJEB14483 at <http://www.ebi.ac.uk/ena/data/view/PRJEB14483>.

### Growth assays

All steps in plasmid loss assays were carried out at 37°C except those shown in Figures 2B and 3B in which all steps were conducted at 30°C or 25°C as indicated. Colonies were grown in LB broth and agar except the assays in Figure 2B and Supplementary Figures 3B and 4 which were performed with a defined rich medium broth and agar containing 0.2% glycerol (Figure 2B) or 0.2% glucose (Supplementary Figures 3B and 4) as a carbon source (60). The plates used in Supplementary Figures 3B and 4 also had decreasing concentrations of aspartate or phenylalanine, as indicated. Strains carrying derivatives of pRC7 were grown in LB broth or defined rich medium with 100 µg ml<sup>-1</sup> of ampicillin overnight, diluted 100-fold into the same type of fresh liquid medium without ampicillin and grown to A<sub>650</sub> 0.4. Dilutions were then plated onto LB or defined rich medium agar plates containing 120 µg ml<sup>-1</sup> X-gal and 1 mM IPTG and incubated for 48 hours except those shown in Figure 2B. Plates were then photographed and scored for blue/white colony formation.

For assays to assess colony forming ability, strains were grown in LB broth overnight at 37°C or, when temperature sensitive strains were involved, at 30°C. Serial 10-fold dilutions were made with 56/2 salts (61) on ice and then 5 µl of each dilution was spotted onto LB agar plates. Plates were then incubated at 37°C for 16 hours. Ampicillin and bicyclomycin were included in LB agar plates where indicated at 100 and 25 µg ml<sup>-1</sup>, respectively.

For the colony formation assays in Supplementary Figure 3A, strains were grown in defined rich medium broth (60) containing 0.2% glucose, all amino acids and 100 µg ml<sup>-1</sup> ampicillin overnight at 37°C. Tenfold serial dilutions were made in 56/2 salts and then 5 µl of each dilution spotted onto defined rich medium plates containing 0.2% glucose, 100 µg ml<sup>-1</sup> ampicillin and with all amino acids or missing either aspartate or phenylalanine. These plates were incubated at 37°C for 16 hours. Minimal medium agar plates (61) were used in Supplementary Figure 3C without and with 100 µg ml<sup>-1</sup> ampicillin as indicated and incubated at 37°C for 72 hours.

Colony-forming ability at increasing doses of UV light was assessed as

described (62). Mismatch repair capacity was measured as the fraction of cells in a culture that acquired spontaneous mutations leading to rifampicin resistance. Briefly, overnight LB cultures were washed once in 56/2 salts and serially diluted tenfold. 100  $\mu$ l of the neat and the  $10^{-1}$  dilution were spread on LB agar containing 15  $\mu$ g  $\text{ml}^{-1}$  rifampicin. To estimate the total cfu  $\text{ml}^{-1}$  in the overnight culture, 10  $\mu$ l of the  $10^{-6}$  dilution was spotted in triplicate on LB agar without rifampicin. Plates were then incubated at 37°C for 16 hours and the colonies then counted.

The liquid growth assays in Figure 2A were performed using a Tecan Infinite M200 Pro plate reader. Overnight LB cultures were diluted to  $A_{600}$  0.005 in LB and 150  $\mu$ l of each culture was transferred into 20 wells of a 96-well flat bottom plate (Corning). The microplate was incubated at 37°C for 24 hours and  $A_{600}$  measurements were performed every 30 minutes preceded by plate shaking.

### **Persistence**

Single colonies were inoculated into 5 ml LB broth and grown with shaking at 37°C overnight. 50  $\mu$ l of overnight culture was then inoculated into 5 ml of LB broth and grown at 37°C with shaking until  $1\text{--}2 \times 10^8$  colony forming units  $\text{ml}^{-1}$  reached. 500  $\mu$ l was then transferred into two 1.5 ml microcentrifuge tubes. The first tube was centrifuged at 6000 rpm for 5 min at room temperature, resuspended in 500  $\mu$ l 56/2 salts, serially diluted tenfold in 56/2 salts and 10  $\mu$ l volumes of the  $10^{-4}$  and  $10^{-5}$  dilutions spotted onto LB agar plates containing 20 mM  $\text{MgSO}_4$  in triplicate. To the second tube 5  $\mu$ l of 10  $\mu$ g  $\text{ml}^{-1}$  ciprofloxacin was added and the tube was then inserted into a 50 ml Falcon tube and placed in a shaking incubator at 37°C for 5 h. After the 5h incubation this tube was centrifuged at 6000 rpm for 5 min at room temperature, resuspended in 500  $\mu$ l 56/2 salts, recentrifuged and resuspended in 500  $\mu$ l 56/2 salts. Colony forming units were then assayed as for the first tube by serial dilution into 56/2 salts and plating in triplicate onto LB agar containing 20 mM  $\text{MgSO}_4$ .  $\text{MgSO}_4$  was included to inhibit the activity of any traces of ciprofloxacin not removed by washing of the cells (63). All plates were incubated at 37°C overnight and then the fraction of colony forming units surviving ciprofloxacin exposure calculated.

### **Flow cytometry**

Analysis of chromosome content after completion of all ongoing rounds of replication, so-called run-out conditions, was performed on mid-log phase cultures after treatment with rifampicin and cephalixin as described (64) using a Becton Coulter CyAn ADP cytometer with 488 nm excitation and a 530/540 nm bandpass filter. Analysis of (p)ppGpp-dependent formation of RpoS-mCherry by flow cytometry was performed by growing the indicated strains overnight in LB, transferring 100  $\mu$ l into 10 ml LB in a 125 ml flask followed by incubation at 37°C for 2h. Then 1 ml of the culture was centrifuged, resuspended in 2 ml of 10% LB in M9 medium and analysed by flow cytometry on a Becton Dickinson LSRFortessa X-20 flow cytometer using 561 nm laser excitation and detection using a 610/620 nm bandpass filter.

### **Translation assays**

$\beta$ -galactosidase activity assays monitoring the relative levels of translation of *cadC-lacZ* fusions were performed in LB broth as described (56).

## Results

### A tRNA mutation suppresses the requirement for accessory replicative helicases

pRC7 is a very low copy plasmid which encodes  $\beta$  lactamase and can therefore be maintained in *E. coli* cells by the inclusion of ampicillin in the medium (65). However, the inefficient origin of replication within pRC7 results in rapid loss of the plasmid in the absence of ampicillin. This rapid loss can be detected if the host strain has a chromosomal deletion of *lacIZYA* since pRC7 encodes the *lac* operon and hence cells with and without the plasmid appear blue and white, respectively, on plates containing IPTG and X-gal (65). This retention or loss of pRC7 can be used to assess whether a gene is essential for colony formation by cloning of the test gene into pRC7, transformation of a  $\Delta lacIZYA$  strain with the pRC7 derivative and subsequent deletion of the test gene from the chromosome. Plating of the strain onto medium containing IPTG and X-gal results in formation of only blue colonies if the test gene is essential or white and segregating colonies if the test gene is not essential (65). Rapid growth of *E. coli* requires accessory helicase activity and so pRC7 encoding *uvrD* can be lost rapidly from  $\Delta lacIZYA rep^+ uvrD^+$  cells on rich medium but pRC7*uvrD* cannot be lost from  $\Delta lacIZYA \Delta rep \Delta uvrD$  cells as monitored by blue/white colony colour (37) (see also Figure 1A, compare i and ii). Spontaneous mutations that suppress this requirement for an accessory helicase can be isolated by exploiting the ability of  $\Delta rep \Delta uvrD$  cells to grow on minimal medium in the absence of a complementing pRC7 plasmid and subsequent plating of plasmid-less cells onto rich medium (37). Rare survivors on rich medium can then form colonies and the mutation(s) responsible for allowing  $\Delta rep \Delta uvrD$  cells to grow under rapid growth conditions can be analysed. We identified one such suppressor, the strain designation of which is N7182 (Supplementary Table 1). Potential linkage of the suppressor mutation to *rep* was tested by transducing  $\Delta rep::cat$  from the suppressor strain into pRC7*uvrD*/*rep*<sup>+</sup>  $\Delta uvrD::dhfr$  (N6639). Eleven chloramphenicol-resistant transductants were tested for loss of pRC7*uvrD* on rich medium. Four transductants could not lose pRC7*uvrD* but seven could, indicating close linkage of the suppressor mutation with  $\Delta rep::cat$  (see also Figure 1A, compare ii and iii).

We sequenced the genome of this suppressor strain and compared it with the genome of N7153, a  $\Delta rep \Delta uvrD$  strain that contains a well-characterised suppressor mutation *rpoB*\*35 (7,12,37,66). Use of the  $\Delta rep \Delta uvrD$  *rpoB*\*35 strain as a reference genome avoided the need for the reference strain to retain a complementing plasmid for viability. Only one mutation in N7182 that was not present in N7153 was located sufficiently close to  $\Delta rep::cat$  to explain the above linkage (see Supplementary File 1). This mutation resulted in replacement of T with C at position 8 within the *aspT* gene, one of three identical tRNA<sup>Asp</sup> genes in *E. coli*. Sequencing of the *aspT* gene from the 11 transductants obtained in the above cross revealed that all seven strains able to lose pRC7*uvrD* contained *aspT*[t8c] whereas all four that could not lose pRC7*uvrD* retained a wild type copy of *aspT*. Suppression of the inviability of  $\Delta rep \Delta uvrD$  cells on rich medium was therefore associated with the *aspT*[t8c] allele, with suppression comparable to that of *rpoB*\*35 in a plasmid loss assay (Fig 1A, compare iii and iv).

$\Delta rep uvrD^+$  cells have a growth defect since UvrD can compensate only partially for the absence of Rep accessory helicase activity, resulting in slower movement of replication forks in  $\Delta rep$  cells (39,40). Thus the median number of copies of *oriC* in  $\Delta rep uvrD^+$  cells is twice that of *rep*<sup>+</sup> *uvrD*<sup>+</sup> cells in rich medium due to an extended cell cycle in  $\Delta rep$  cells and hence more replication initiation events per cell cycle (38). This doubling in *oriC* numbers results in a doubling of chromosome content when cells are treated with cephalixin and rifampicin to inhibit cell division and reinitiation of replication, so-called run-out conditions (38) (see also Figure 1B, compare i and iii). *aspT*[t8c] suppressed the increased chromosome copy

number in  $\Delta rep\ uvrD^+$  cells, reducing the median number of chromosomes from eight to four (Figure 1B, compare iii and iv). These data support the conclusion that this tRNA mutation reduces the need for accessory helicase activity. Furthermore, *aspT[t8c]* had no detectable impact on other UvrD-mediated processes. Defects in nucleotide excision repair, mismatch repair and control of recombination in *rep^+*  $\Delta uvrD$  cells (52,67,68) were not suppressed by *aspT[t8c]* (Supplementary Figure 1A, B and C, respectively), providing further support for the specific suppression of the accessory helicase defect in  $\Delta rep\ \Delta uvrD$  cells by *aspT[t8c]*.

The requirement for accessory helicase activity is driven primarily by transcriptional barriers to replication (22,37). Backtracking of paused RNA polymerases results in formation of particularly stable replicative barriers and multiple factors have evolved to reduce the numbers of backtracked complexes (7). Cells lacking two homologous anti-backtracking factors, GreA and GreB, display a temperature-sensitive growth defect that is a consequence of more frequent collisions between replisomes and backtracked transcription complexes (7,12,69). *aspT[t8c]* suppressed the temperature-sensitive phenotype of  $\Delta greA\ \Delta greB$  cells (Figure 1C), similar to the suppression seen with *rpoB\*35* (48). We conclude that *aspT[t8c]* reduces the need for GreA/GreB-dependent rescue of backtracked RNA polymerase.

Taken together, these data indicate that *aspT[t8c]* reduces the need for Rep and UvrD to underpin replication and for anti-backtracking factors to resuscitate transcription complexes.

### **Suppression by *aspT[t8c]* does not occur via growth rate restriction**

The uridine encoded at position 8 within the wild type *aspT* gene is post-transcriptionally modified to 4-thiouridine and this modified nucleotide is conserved across all kingdoms of life (70). This residue is involved in a triple non-Watson-Crick pairing interaction and is important in coordination of magnesium within tRNA (71,72). This central structural role is reflected in the temperature-dependent destabilisation of human mitochondrial tRNA<sup>Met</sup> structure by the same T to C mutation as found in *aspT[t8c]*. This transition mutation in tRNA<sup>Met</sup> inhibits aminoacylation and any mutated tRNA<sup>Met</sup> that is aminoacylated fails to form a stable ternary complex with elongation factor EF-Tu (70).

Given the conservation of tRNA structure, *aspT[t8c]* may result in similar structural destabilisation of the encoded tRNA<sup>Asp</sup> and consequent inhibition of interactions with aspartyl tRNA synthetase and EF-Tu. However, *aspT[t8c]* did not have a major impact on growth of *rep^+ uvrD^+* cells in liquid culture (Figure 2A, compare i and ii). This absence of a significant growth defect in *aspT[t8c]* strains may be due to the presence of two other identical tRNA<sup>Asp</sup> genes in *E. coli*, *aspU* and *aspV*.

Other means of growth restriction did not suppress  $\Delta rep\ \Delta uvrD$  inviability. Growth on defined rich medium containing all 20 amino acids but with a poor carbon source, glycerol, did not result in suppression of  $\Delta rep\ \Delta uvrD\ aspT^+$  inviability at either 37°C or 25°C as determined using a plasmid loss assay (Figure 2B). Reduced growth rates therefore do not provide a general means of reducing the need for accessory helicase activity.

### **Defective tRNA aminoacylation suppresses $\Delta rep\ \Delta uvrD$ inviability**

As reduced growth rate was not the cause of suppression by *aspT[t8c]*, we probed whether defective translation was responsible. We could not detect significant defects in translation *in vivo* at tandem aspartate codons in an *aspT[t8c]* strain (Supplementary Figure 2). Either this allele does not result in translational pausing or such pausing is below the limits of detection using this assay. We therefore used alternative approaches to probe the *aspT[t8c]* suppression mechanism. The same t8c mutation in human mitochondrial tRNA<sup>Met</sup> inhibits aminoacylation (70). Inhibition

of tRNA<sup>Asp</sup> aminoacylation was therefore tested for suppression of  $\Delta rep \Delta uvrD$  lethality. The *E. coli tls-1* allele encodes a P555S mutation in aspartyl tRNA synthetase that reduces the thermal stability of the synthetase and causes a severe reduction in growth rate at 42°C under low salt conditions (73,74) (see also Figure 3A). Given that AspRS<sup>P555S</sup> is less stable than wild type enzyme regardless of the temperature (74), we tested whether *aspS*<sup>P555S</sup> suppressed  $\Delta rep \Delta uvrD$  lethality at 30°C on low salt medium, conditions under which viability is similar to wild type (73) (see also Figure 3A, compare i and ii). pRC7*uvrD* could be lost from  $\Delta rep \Delta uvrD$  *aspS*<sup>P555S</sup> at 30°C on low salt medium but not on high salt medium (Figure 3Biii). Suppression of  $\Delta rep \Delta uvrD$  lethality correlates therefore with a defect in aspartyl tRNA synthetase.

We also tested whether an alternative means of inhibiting tRNA<sup>Asp</sup> aminoacylation could suppress  $\Delta rep \Delta uvrD$  inviability. A pRC7*uvrD*/ $\Delta rep \Delta uvrD$  strain defective in aspartate biosynthesis could lose the complementing pRC7*uvrD* plasmid on defined rich medium upon restriction of aspartate availability (Supplementary Figure 3). Thus a defect in the enzyme needed to synthesise aspartyl tRNA, AspRS, or a limiting concentration of one of the substrates needed for formation of aspartyl tRNA, aspartate, can suppress the need for accessory replicative helicase activity. Moreover, suppression was not specific to aspartate starvation as restriction of availability of phenylalanine also allowed  $\Delta rep \Delta uvrD$  cells to survive in the absence of a complementing plasmid (Supplementary Figure 4). As expected, restricting amino acid availability also resulted in very poor growth (Supplementary Figures 3 and 4) but a restricted growth rate does not by itself provide suppression of  $\Delta rep \Delta uvrD$  lethality (Figure 2B). These data support the conclusion that inhibition of aminoacylation of tRNA<sup>Asp</sup>, and of other tRNAs, reduces the need for accessory helicase activity.

### **Translational pausing suppresses $\Delta rep \Delta uvrD$ inviability**

Suppression of  $\Delta rep \Delta uvrD$  inviability via inhibition of tRNA<sup>Asp</sup> or tRNA<sup>Phe</sup> aminoacylation might occur directly via pausing of ribosomes but could also occur via decreased production of one or more specific proteins containing both aspartate and phenylalanine. We tested therefore whether increased translational pausing by a well-defined mechanism that does not rely on decreased tRNA aminoacylation also suppresses the need for accessory helicase activity. Peptide bond formation by ribosomes occurs with low efficiency within polyproline tracts as compared with other amino acids and this low efficiency is compensated for by interaction of elongation factor P (EF-P) with the ribosome (56,75). When EF-P is absent ( $\Delta efp$ ) ribosomes pause for extended periods at tandem proline codons (56,75) (see also Supplementary Figure 2) resulting in reduced growth rates (76) (see also Figure 2A). Despite its negative effect on growth rate, introduction of  $\Delta efp$  clearly suppresses  $\Delta rep \Delta uvrD$  lethality (Figure 4, compare A and B). *yjeA* and *yjeK* encode enzymes needed for post-translational modification of EF-P to form fully functional enzyme (56,75-78) and deletion of either *yjeA* or *yjeK* also resulted in suppression (Figure 4C and D). Enhancement of ribosomal pausing at polyproline sequences can therefore reduce the need for accessory helicase activity.

### **Suppression by *aspT*[t8c] and $\Delta efp$ requires (p)ppGpp synthesis**

One consequence of ribosomal pausing is increased synthesis of (p)ppGpp by RelA upon binding of RelA to a ribosome containing a non-acylated tRNA in the A site (15,16). Elevated (p)ppGpp is known to suppress  $\Delta rep \Delta uvrD$  inviability (37) and so *aspT*[t8c] and  $\Delta efp$  might both therefore suppress via elevation of (p)ppGpp concentration.

Direct measurement of (p)ppGpp using <sup>32</sup>P cannot be performed on cells grown in rich media (79) which prevents direct assessment of (p)ppGpp levels in *aspT*[t8c] and  $\Delta efp$  strains under conditions relevant to suppression of  $\Delta rep \Delta uvrD$  lethality. An

indirect assay was therefore used that employs an RpoS-mCherry translational fusion (34). This reporter provides a fluorescence signal that correlates with intracellular (p)ppGpp concentration due to (p)ppGpp both stimulating *rpoS* transcription and inhibiting RpoS degradation (34). Fluorescence was assayed by flow cytometry of cells grown to mid-logarithmic phase in rich medium. *relA*<sup>+</sup> *spoT*<sup>+</sup> cells lacking the RpoS-mCherry fusion and *rpoS-mCherry ΔrelA ΔspoT* cells which are unable to synthesise (p)ppGpp gave similar levels of background fluorescence (Figure 5Ai and ii). An increase in fluorescence was observed in wild type cells carrying the fusion but this increase was modest (Figure 5A, compare iii with i and ii), consonant with low (p)ppGpp levels in wild type cells growing in nutrient-rich environments (34,80). mCherry fluorescence increased substantially in *Δefp* cells but not in *aspT[t8c]* cells with respect to wild type (Figure 5A, compare iv and v with iii). We conclude that absence of EF-P results in elevation of (p)ppGpp concentration. Higher (p)ppGpp concentration in *Δefp* cells as compared with wild type or *aspT[t8c]* cells is consistent with the significant retardation of growth of *Δefp* cells (Figure 2A). In contrast, *aspT[t8c]* either does not increase (p)ppGpp levels as compared with wild type cells or any increase is below the limits of detection using this assay. To gauge the sensitivity of this assay we monitored fluorescence in *spoT1* cells. *spoT1* encodes a SpoT enzyme that retains (p)ppGpp synthase activity but lacks (p)ppGpp pyrophosphorylase activity, resulting in elevated (p)ppGpp (81) and the ability to suppress *Δrep ΔuvrD* lethality (37). *spoT1 rpoS-mCherry* cells did not result in increased fluorescence as compared with *spoT*<sup>+</sup> *rpoS-mCherry* cells indicating that (p)ppGpp levels sufficient to reduce the need for accessory replicative helicases could go undetected using this assay (Figure 5Aii and vi).

To address this potential sensitivity problem we employed a second assay to determine whether either *Δefp* or *aspT[t8c]* results in elevated (p)ppGpp. Cells with elevated (p)ppGpp display elevated levels of persistence and thus *spoT1* enhances whereas *ΔrelA ΔspoT* alleles reduce persistence (34,82) (see also Figure 5Bi-iii). *aspT[t8c]* and *Δefp* both increased persistence with the increase being higher for *Δefp* (Figure 5Biv and v). The large increase in persistence in *Δefp* cells correlates with the enhancement of fluorescence in *Δefp rpoS-mCherry* cells. The level of persistence in *aspT[t8c]* cells is consistent with a smaller increase in (p)ppGpp levels as compared with *Δefp* that is below the limits of detection in the mCherry fluorescence assay.

We tested whether increased (p)ppGpp contributed to suppression of *Δrep ΔuvrD* inviability by *aspT[t8c]* and *Δefp* by deleting the gene encoding the primary (p)ppGpp synthase, *relA*. Deletion of *relA* prevented loss of pRC7uvrD from *Δrep ΔuvrD aspT[t8c]* and *Δrep ΔuvrD Δefp* cells, indicating that RelA was required for suppression by both mutant alleles (Figure 5C, compare iii with iv and v with vi). In contrast, pRC7uvrD could be lost from *Δrep ΔuvrD ΔrelA rpoB\*35* cells indicating that RelA was not required for the viability of suppressed *Δrep ΔuvrD* strains under all circumstances (Figure 5C, compare vii and viii). This lack of dependence of *Δrep ΔuvrD rpoB\*35* on RelA likely reflects the recapitulation by *rpoB\*35* of many phenotypes associated with elevated (p)ppGpp even in the absence of RelA (48,66).

Taken together, these data indicate that RelA-directed synthesis of (p)ppGpp is important for suppression of *Δrep ΔuvrD* lethality by both *aspT[t8c]* and *Δefp*.

### ***aspT[t8c]* and *Δefp* confer differing requirements for Rho activity**

Translocation 5'-3' by Rho along untranslated and unstructured nascent transcripts can displace transcription complexes thus reducing both RNA polymerase occupancy on the chromosome and R-loop formation (11,83,84). Rep and Rho therefore provide two different mechanisms that reduce the impact of transcription on replication. Consequently, cells need either Rep or wild type levels of Rho activity to maintain genome duplication in the face of transcriptional barriers (10,85). One manifestation of this requirement is the hypersensitivity of *Δrep uvrD*<sup>+</sup> cells to low concentrations of



the Rho-specific inhibitor bicyclomycin (10) (see also Figure 6A and B, compare i and iii).

We assessed whether  $\Delta efp$  or  $aspT[t8c]$  could suppress  $\Delta rep$  bicyclomycin hypersensitivity. Neither  $\Delta efp$  nor  $aspT[t8c]$  altered bicyclomycin sensitivity in a  $rep^+$  background (Figure 6A and B, compare i and ii). In  $\Delta rep$  cells hypersensitivity was suppressed by  $\Delta efp$  but not by  $aspT[t8c]$  (Figure 6A and B, compare iii and iv). These data demonstrate that  $\Delta efp$  but not  $aspT[t8c]$  can reduce the requirement for Rho activity in the absence of Rep.

We also tested whether this differential need for Rho activity was reflected in cells lacking both  $rep$  and  $uvrD$  by exploiting  $rho[A243E]$  which encodes a partial loss of function enzyme (86). Rho dependency was assessed by the ability of  $\Delta rep \Delta uvrD$  strains to lose a complementing pRC7 $rep$  rather than pRC7 $uvrD$  plasmid, allowing construction of pRC7 $rep/\Delta rep \Delta uvrD rho[A243E]$  strains regardless of  $rep rho$  double mutant lethality (85). The similar numbers and sizes of white plasmidless colonies formed by  $\Delta rep \Delta uvrD \Delta efp rho^+$  and  $\Delta rep \Delta uvrD \Delta efp rho[A243E]$  cells indicate that wild type Rho function was not required for suppression by  $\Delta efp$  (Figure 6C, compare v and vi). In contrast,  $\Delta rep \Delta uvrD aspT[t8c] rho[A243E]$  gave much smaller white plasmidless colonies as compared with the isogenic  $rho^+$  strain indicating that wild type Rho function was important for growth of  $aspT[t8c] \Delta rep \Delta uvrD$  cells (Figure 6C, compare iii and iv).

The data in Figures 5 and 6 indicate that the viability of  $aspT[t8c] \Delta rep \Delta uvrD$  cells requires both the major (p)ppGpp synthase in the cell, RelA, and wild type Rho activity. In contrast,  $\Delta efp \Delta rep \Delta uvrD$  cells require RelA but not wild type Rho activity.  $\Delta efp$  cells have higher levels of (p)ppGpp as compared with  $aspT[t8c]$  (Figure 5A) and these elevated levels might explain the differential requirement for Rho, given the ability of (p)ppGpp to reduce replication/transcription conflicts (12,37,66). Such a model implies that (p)ppGpp synthesis is critical not only for the viability of  $\Delta efp \Delta rep \Delta uvrD$  cells (Figure 5C) but also for suppression of bicyclomycin sensitivity of  $\Delta rep$  cells (Figure 6A). Absence of the primary (p)ppGpp synthase RelA did not hypersensitise otherwise wild type cells to bicyclomycin (Figure 7Aiii). However, the suppression of  $\Delta rep$  bicyclomycin hypersensitivity by  $\Delta efp$  was abolished upon deletion of  $relA$  (Figure 7A, compare viii with v). Thus RelA-dependent (p)ppGpp synthesis in  $\Delta rep \Delta efp$  cells is essential for survival with lowered Rho activity, supporting the hypothesis that elevated (p)ppGpp can reduce the need for Rho.

We tested this possible link between (p)ppGpp concentration and requirement for Rho by determining whether other means of increasing (p)ppGpp concentration can reduce the need for Rho activity in  $\Delta rep$  cells. The  $spoT1$  allele suppressed  $\Delta rep$  bicyclomycin hypersensitivity supporting the conclusion that elevated (p)ppGpp can reduce the need for Rho (Figure 7B, compare iv with ii).

The data in Figures 5-7 indicate that both  $aspT[t8c]$  and  $\Delta efp$  require RelA-directed synthesis of (p)ppGpp to maintain the viability of  $\Delta rep \Delta uvrD$  cells. In contrast,  $\Delta efp$  has a much lower dependence on Rho activity as compared with  $aspT[t8c]$ . This differential requirement for Rho activity correlates with higher (p)ppGpp levels in  $\Delta efp$  cells as compared with  $aspT[t8c]$ . Resolving conflicts between replication and transcription involves therefore a fine balance between accessory replicative helicases, levels of (p)ppGpp and Rho activity.

## Discussion

We have discovered three new types of suppressors of  $\Delta rep \Delta uvrD$  rich medium lethality: mutations in tRNA genes, in aminoacyl-tRNA synthetases and in translation elongation factors. Whilst the mechanistic consequences of the  $aspT[t8c]$  mutation are unclear, the inhibition of tRNA aminoacylation by  $aspS^{P555S}$  and of translation elongation by  $\Delta efp$  are well-characterised (56,74,75), indicating that partial inhibition of translation can suppress  $\Delta rep \Delta uvrD$  lethality. Previous studies have demonstrated that this lethality is caused primarily by the conflict between

replication and transcription (22,37,54). Thus partial inhibition of translation can compensate for the impact of transcription on DNA replication in the absence of Rep and UvrD. Suppression requires RelA-directed synthesis of (p)ppGpp with (p)ppGpp concentration being higher with  $\Delta efp$  than with  $aspT[t8c]$  (Figure 5). Wild type levels of Rho activity are also needed in  $aspT[t8c] \Delta rep \Delta uvrD$  but not  $\Delta efp \Delta rep \Delta uvrD$  cells indicating that the relative importance of (p)ppGpp and Rho function depends upon the nature of the translational mutation (Figure 6).

$\Delta rep \Delta uvrD$  cells are inviable on rich medium primarily because of lack of accessory replicative helicase function (22,37,54). Suppression of this growth defect by the above translation mutations (Figures 1A, 3B and 4) therefore suggest that it is the lack of accessory helicase activity in  $\Delta rep \Delta uvrD$  cells that is being suppressed. Suppression by  $aspT[t8c]$  of the chromosome content defect of  $\Delta rep$  cells, a direct consequence of slower fork movement in the absence of Rep accessory helicase activity (37-39), supports this view (Figure 1B). UvrD also inhibits RecFOR-dependent loading of RecA at blocked replication forks (52,68) and absence of this function makes a minor contribution to  $\Delta rep \Delta uvrD$  lethality (22,37,53). However, the lack of suppression of this RecA displacement defect by  $aspT[t8c]$  (Supplementary Figure 1C) indicates that suppression of  $\Delta rep \Delta uvrD$  lethality by  $aspT[t8c]$  does not operate via an effect on RecA loading. UvrD might also aid replication of transcribed DNA by inducing backtracking of RNAP stalled at DNA lesions, one consequence of which may be to promote repair of the lesion and allow the RNAP to then continue transcription (14). However,  $\Delta rep \Delta uvrA$  cells, lacking nucleotide excision repair, are viable (54) indicating that lesion repair via UvrD-catalysed backtracking of RNAP cannot be a major contributor to  $\Delta rep \Delta uvrD$  lethality.  $aspT[t8c]$  also does not suppress the sensitivity of  $\Delta uvrD$  cells to UV light indicating that  $aspT[t8c]$  does not suppress nucleotide excision repair defects (Supplementary Figure 1A). Furthermore,  $aspT[t8c]$  suppression of the  $\Delta greA \Delta greB$  growth defect indicates that  $aspT[t8c]$  can suppress the absence of an *anti*-backtracking activity, making it difficult to explain how  $aspT[t8c]$  could also suppress the absence of a UvrD *pro*-backtracking function (Figure 1C).

RelA-directed synthesis of (p)ppGpp plays a central role in maintaining  $\Delta rep \Delta uvrD$  viability by  $aspT[t8c]$  and by  $\Delta efp$  (Figure 5C). (p)ppGpp dramatically inhibits transcription of *rrn* operons (19) which are the primary transcriptional barriers to genome duplication (21,24), together with other highly expressed operons (20). (p)ppGpp may also destabilise stalled RNAP (12) or increase the fidelity of transcription (25), both of which could decrease the impact of transcription on fork movement.  $aspT[t8c]$ - and  $\Delta efp$ -directed suppression of  $\Delta rep \Delta uvrD$  lethality via (p)ppGpp is therefore likely to occur by impacting on transcription initiation, stalled RNAP stability and/or decreased pausing due to enhanced fidelity.

RelA is stimulated to synthesise (p)ppGpp when an uncharged cognate tRNA is bound to the ribosomal A site (15,16).  $aspT[t8c]$  and  $\Delta efp$  mutations may therefore increase the probability of A site-bound uncharged tRNA either directly or indirectly. The uridine at position 8 is highly conserved in tRNA species and the equivalent *t8c* mutation within human mitochondrial tRNA<sup>Met</sup> results in inhibition of tRNA aminoacylation (70). If  $aspT[t8c]$  also resulted in inhibition of aminoacylation then the resulting increase in non-acylated tRNA<sup>Asp</sup> could lead to an increased probability of uncharged tRNA<sup>Asp</sup> occupying the ribosomal A site. However, whether the mutant tRNA<sup>Asp</sup> can still bind to the A site is unknown. Alternatively tRNA<sup>asp[t8c]</sup> might poison the aspartyl tRNA synthetase by binding to it and forming a dead end complex with respect to aminoacylation. Formation of such a dead end complex might titrate out aspartyl tRNA synthetase and increase levels of uncharged wild type tRNA<sup>Asp</sup> leading to increased non-acylated tRNA<sup>Asp</sup> occupying the ribosomal A site. For cells lacking EF-P, YjeA or YjeK it is difficult to conceive how a reduced rate of proline-proline bond formation within the ribosome could lead directly to increased

occupancy of the A site by uncharged tRNA. Absence of any one of these three factors, though, does impact on expression of many genes and so altered expression of one or more genes in  $\Delta efp$ ,  $\Delta yjeA$  or  $\Delta yjeK$  cells could result in an increased probability of A site-bound uncharged tRNA. For example,  $\Delta efp$  cells have reduced expression of valyl tRNA synthetase (87) which could lead to accumulation of uncharged tRNA<sup>Val</sup> and triggering of the stringent response. Suppression of  $\Delta rep \Delta uvrD$  lethality by  $aspS^{P555S}$  demonstrates that suppression via partial loss of tRNA synthetase function can occur (Figure 3).

In contrast to the requirement for RelA to sustain suppression of  $\Delta rep \Delta uvrD$  lethality by both  $aspT[t8c]$  and  $\Delta efp$ , the requirement for Rho activity is reduced in  $\Delta efp$  as compared with  $aspT[t8c]$  cells (Figures 6 and 7). This difference correlates with the higher concentration of (p)ppGpp in  $\Delta efp$  as compared with  $aspT[t8c]$  cells (Figure 5). A role for (p)ppGpp in reducing the need for Rho activity is supported by the ability of  $spoT1$  to suppress  $\Delta rep$  bicyclomycin hypersensitivity (Figure 7B). Suppression of  $\Delta rep$  bicyclomycin hypersensitivity by  $\Delta efp$  also depends on RelA which supports a critical balance between (p)ppGpp concentration and Rho activity in maintaining viability (Figure 7A). Elevated (p)ppGpp can therefore reduce the need for Rho.

The greater dependence of  $aspT[t8c]$ -directed suppression on Rho might reflect not just lower (p)ppGpp levels in  $aspT[t8c]$  versus  $\Delta efp$  cells but possibly also enhancement of Rho binding on nascent transcripts by  $aspT[t8c]$ . In other words, suppression via  $aspT[t8c]$  might occur at least partly via the increased generation of Rho binding sites on emerging transcripts. Aspartate codons are more frequent than polyproline tracts and hence  $aspT[t8c]$  has the potential to impact on ribosome translocation more frequently than  $\Delta efp$ . Enhancement of Rho binding would also be dependent only on ribosomal pausing and not specifically require ribosomal A site occupancy by a non-aminoacylated tRNA (88), in contrast to stimulation of RelA activity (15,16). However, any  $aspT[t8c]$ -directed increase of transcription complex displacement by Rho cannot be sufficient by itself to suppress  $\Delta rep \Delta uvrD$  lethality since RelA is also needed (Figure 5C).

Our data indicate that whilst translation helps prevent RNAP backtracking (7,9) the reduction of conflicts between replication and transcription can be achieved more effectively by partial inhibition of translation. Of course, the growth defect in  $\Delta efp$  cells (Figure 2A) indicates why the balance between replication, transcription, translation and (p)ppGpp synthesis is poised as it is in wild type cells. Thus for the maintenance of rapid growth there is a very fine balance to be struck between gene expression and accurate, rapid genome duplication. Furthermore, accessory replicative helicases play a major role in determining this balance. In the absence of both Rep and UvrD the wild type balance between various other mechanisms that reduce the impact of transcription on replication is unable to effectively counter the adverse effects of transcription on completion of genome duplication. There may also be circumstances under which mutations such as those identified here confer a selective advantage even in  $rep^+ uvrD^+$  cells. Elevated (p)ppGpp is a key factor in determining bacterial persistence in the face of antibiotic challenge (34) and both  $aspT[t8c]$  and  $\Delta efp$  mutations enhance persistence (Figure 5B). It remains possible therefore that mutations such as  $aspT[t8c]$  that have only a modest inhibitory effect on growth could arise in bacterial populations continually exposed to antibiotics, especially given the many mutations known to affect translation (89). Increased persistence in strains lacking EF-P function also imply that EF-P and its unique post-translational modification pathway are poor potential targets for antibiotics.

**Accession numbers**

Sequencing data were submitted in form of fastq files to the European Nucleotide Archive (ENA) and are available under accession number PRJEB14483 at <http://www.ebi.ac.uk/ena/data/view/PRJEB14483>.

**Supplementary data**

Supplementary data are available at NAR Online.

**Funding**

This work was funded by the UK Biotechnology and Biological Sciences Research Council (BBSRC) to PM [grant numbers BB/I001859/2 and BB/J014826/1] and to NJS and MSD [grant number BB/I003142/1], and by the UK Medical Research Council (MRC) to RGL [grant number G0800970].

**Conflict of interest**

The authors declare there are no conflicts of interest.

**Acknowledgements**

We would like to thank Lynne Charlwood for constructing strains LC035 and LC037, Kenn Gerdes, Etienne Maisonneuve and Heath Murray for help with initial experiments using *rpoS-mCherry*, Akeel Mahdi and Carol Buckman for sequencing the *aspT* alleles of transductants during initial suppressor mapping and Karen Hogg in the University of York Biosciences Technology Facility for help with flow cytometry. We also thank J. Gowrishankar, Kenn Gerdes, Etienne Maisonneuve and Gilbert Eriani for supplying strains, Kirsten Jung for supplying p3LC-TL30-5P and p3LC-TL30-5D and Robert Washburn and Max Gottesman for supplying bicyclomycin.

## References

1. Brewer, B.J. (1988) When polymerases collide: replication and the transcriptional organization of the *E. coli* chromosome. *Cell*, **53**, 679-686.
2. Rudolph, C.J., Dhillon, P., Moore, T. and Lloyd, R.G. (2007) Avoiding and resolving conflicts between DNA replication and transcription. *DNA Repair (Amst)*, **6**, 981-993.
3. McGlynn, P., Savery, N.J. and Dillingham, M.S. (2012) The conflict between DNA replication and transcription. *Mol. Microbiol.*, **85**, 12-20.
4. Helmrich, A., Ballarino, M., Nudler, E. and Tora, L. (2013) Transcription-replication encounters, consequences and genomic instability. *Nat. Struct. Mol. Biol.*, **20**, 412-418.
5. Landick, R. (2006) The regulatory roles and mechanism of transcriptional pausing. *Biochem. Soc. Trans.*, **34**, 1062-1066.
6. Komissarova, N. and Kashlev, M. (1997) RNA polymerase switches between inactivated and activated states by translocating back and forth along the DNA and the RNA. *J. Biol. Chem.*, **272**, 15329-15338.
7. Dutta, D., Shatalin, K., Epshtein, V., Gottesman, M.E. and Nudler, E. (2011) Linking RNA polymerase backtracking to genome instability in *E. coli*. *Cell*, **146**, 533-543.
8. Epshtein, V. and Nudler, E. (2003) Cooperation between RNA polymerase molecules in transcription elongation. *Science*, **300**, 801-805.
9. Proshkin, S., Rahmouni, A.R., Mironov, A. and Nudler, E. (2010) Cooperation between translating ribosomes and RNA polymerase in transcription elongation. *Science*, **328**, 504-508.
10. Washburn, R.S. and Gottesman, M.E. (2011) Transcription termination maintains chromosome integrity. *Proc. Natl. Acad. Sci. U S A*, **108**, 792-797.
11. Krishna Leela, J., Syeda, A.H., Anupama, K. and Gowrishankar, J. (2013) Rho-dependent transcription termination is essential to prevent excessive genome-wide R-loops in *Escherichia coli*. *Proc. Natl. Acad. Sci. U S A*, **110**, 258-263.
12. Trautinger, B.W., Jaktaji, R.P., Rusakova, E. and Lloyd, R.G. (2005) RNA polymerase modulators and DNA repair activities resolve conflicts between DNA replication and transcription. *Mol. Cell*, **19**, 247-258.
13. Orlova, M., Newlands, J., Das, A., Goldfarb, A. and Borukhov, S. (1995) Intrinsic transcript cleavage activity of RNA polymerase. *Proc. Natl. Acad. Sci. U. S. A.*, **92**, 4596-4600.
14. Epshtein, V., Kamarthapu, V., McGary, K., Svetlov, V., Ueberheide, B., Proshkin, S., Mironov, A. and Nudler, E. (2014) UvrD facilitates DNA repair by pulling RNA polymerase backwards. *Nature*, **505**, 372-377.
15. Haseltine, W.A. and Block, R. (1973) Synthesis of guanosine tetra- and pentaphosphate requires the presence of a codon-specific, uncharged transfer ribonucleic acid in the acceptor site of ribosomes. *Proc. Natl. Acad. Sci. U S A*, **70**, 1564-1568.
16. Wendrich, T.M., Blaha, G., Wilson, D.N., Marahiel, M.A. and Nierhaus, K.H. (2002) Dissection of the mechanism for the stringent factor RelA. *Mol. Cell*, **10**, 779-788.
17. Potrykus, K. and Cashel, M. (2008) (p)ppGpp: still magical? *Annu. Rev. Microbiol.*, **62**, 35-51.
18. Battesti, A. and Bouveret, E. (2006) Acyl carrier protein/SpoT interaction, the switch linking SpoT-dependent stress response to fatty acid metabolism. *Mol. Microbiol.*, **62**, 1048-1063.
19. Barker, M.M., Gaal, T., Josaitis, C.A. and Gourse, R.L. (2001) Mechanism of regulation of transcription initiation by ppGpp. I. Effects of ppGpp on transcription initiation *in vivo* and *in vitro*. *J. Mol. Biol.*, **305**, 673-688.

20. Durfee, T., Hansen, A.M., Zhi, H., Blattner, F.R. and Jin, D.J. (2008) Transcription profiling of the stringent response in *Escherichia coli*. *J. Bacteriol.*, **190**, 1084-1096.
21. Ton-Hoang, B., Pasternak, C., Siguier, P., Guynet, C., Hickman, A.B., Dyda, F., Sommer, S. and Chandler, M. (2010) Single-stranded DNA transposition is coupled to host replication. *Cell*, **142**, 398-408.
22. Boubakri, H., de Septenville, A.L., Viguera, E. and Michel, B. (2010) The helicases DinG, Rep and UvrD cooperate to promote replication across transcription units *in vivo*. *EMBO J.*, **29**.
23. Srivatsan, A., Tehranchi, A., MacAlpine, D.M. and Wang, J.D. (2010) Co-orientation of replication and transcription preserves genome integrity. *PLoS Genet.*, **6**, e1000810.
24. Merrikh, H., Machon, C., Grainger, W.H., Grossman, A.D. and Souttanas, P. (2011) Co-directional replication-transcription conflicts lead to replication restart. *Nature*, **470**, 554-557.
25. Roghanian, M., Zenkin, N. and Yuzenkova, Y. (2015) Bacterial global regulators DksA/ppGpp increase fidelity of transcription. *Nucleic Acids Res.*, **43**, 1529-1536.
26. Kamarthapu, V., Epshtein, V., Benjamin, B., Proshkin, S., Mironov, A., Cashel, M. and Nudler, E. (2016) ppGpp couples transcription to DNA repair in *E. coli*. *Science*, **352**, 993-996.
27. Wang, J.D., Sanders, G.M. and Grossman, A.D. (2007) Nutritional control of elongation of DNA replication by (p)ppGpp. *Cell*, **128**, 865-875.
28. Maciag, M., Kochanowska, M., Lyzen, R., Wegrzyn, G. and Szalewska-Palasz, A. (2010) ppGpp inhibits the activity of *Escherichia coli* DnaG primase. *Plasmid*, **63**, 61-67.
29. Maciag-Dorszynska, M., Szalewska-Palasz, A. and Wegrzyn, G. (2013) Different effects of ppGpp on *Escherichia coli* DNA replication *in vivo* and *in vitro*. *FEBS Open Bio.*, **3**, 161-164.
30. Denapoli, J., Tehranchi, A.K. and Wang, J.D. (2013) Dose-dependent reduction of replication elongation rate by (p)ppGpp in *Escherichia coli* and *Bacillus subtilis*. *Mol. Microbiol.*, **88**, 93-104.
31. Rojas, A.M., Ehrenberg, M., Andersson, S.G. and Kurland, C.G. (1984) ppGpp inhibition of elongation factors Tu, G and Ts during polypeptide synthesis. *Mol. Gen. Genet.*, **197**, 36-45.
32. Kanjee, U., Ogata, K. and Houry, W.A. (2012) Direct binding targets of the stringent response alarmone (p)ppGpp. *Mol. Microbiol.*, **85**, 1029-1043.
33. Brauner, A., Fridman, O., Gefen, O. and Balaban, N.Q. (2016) Distinguishing between resistance, tolerance and persistence to antibiotic treatment. *Nat. Rev. Microbiol.*, **14**, 320-330.
34. Maisonneuve, E., Castro-Camargo, M. and Gerdes, K. (2013) (p)ppGpp Controls Bacterial Persistence by Stochastic Induction of Toxin-Antitoxin Activity. *Cell*, **154**, 1140-1150.
35. Bochman, M.L., Sabouri, N. and Zakian, V.A. (2010) Unwinding the functions of the Pif1 family helicases. *DNA Repair (Amst)*, **9**, 237-249.
36. Bruning, J.G., Howard, J.L. and McGlynn, P. (2014) Accessory Replicative Helicases and the Replication of Protein-Bound DNA. *J. Mol. Biol.*, **426**, 3917-3928.
37. Guy, C.P., Atkinson, J., Gupta, M.K., Mahdi, A.A., Gwynn, E.J., Rudolph, C.J., Moon, P.B., van Knippenberg, I.C., Cadman, C.J., Dillingham, M.S. *et al.* (2009) Rep Provides a Second Motor at the Replisome to Promote Duplication of Protein-Bound DNA. *Mol. Cell*, **36**, 654-666.
38. Gupta, M.K., Guy, C.P., Yeeles, J.T., Atkinson, J., Bell, H., Lloyd, R.G., Mariani, K.J. and McGlynn, P. (2013) Protein-DNA complexes are the

- primary sources of replication fork pausing in *Escherichia coli*. *Proc. Natl. Acad. Sci. U S A*, **110**, 7252-7257.
39. Lane, H.E. and Denhardt, D.T. (1975) The rep mutation. IV. Slower movement of replication forks in *Escherichia coli* rep strains. *J. Mol. Biol.*, **97**, 99-112.
  40. Atkinson, J., Gupta, M.K., Rudolph, C.J., Bell, H., Lloyd, R.G. and McGlynn, P. (2011) Localization of an accessory helicase at the replisome is critical in sustaining efficient genome duplication. *Nucleic Acids Res.*, **39**, 949-957.
  41. Uzest, M., Ehrlich, S.D. and Michel, B. (1995) Lethality of rep recB and rep recC double mutants of *Escherichia coli*. *Mol. Microbiol.*, **17**, 1177-1188.
  42. Michel, B., Ehrlich, S.D. and Uzest, M. (1997) DNA double-strand breaks caused by replication arrest. *EMBO J.*, **16**, 430-438.
  43. Seigneur, M., Bidnenko, V., Ehrlich, S.D. and Michel, B. (1998) RuvAB acts at arrested replication forks. *Cell*, **95**, 419-430.
  44. Syeda, A.H., Atkinson, J., Lloyd, R.G. and McGlynn, P. (2016) The Balance between Recombination Enzymes and Accessory Replicative Helicases in Facilitating Genome Duplication. *Genes*, **7**.
  45. Atkinson, J., Gupta, M.K. and McGlynn, P. (2011) Interaction of Rep and DnaB on DNA. *Nucleic Acids Res.*, **39**, 1351-1359.
  46. Taucher-Scholtz, G., Abdel-Monem, M. and Hoffmann-Berling, H. (1983) In Cozzarelli, N. R. (ed.), *Mechanisms of DNA replication and recombination*. Alan R. Liss Inc., New York, pp. 65-76.
  47. Baharoglu, Z., Lestini, R., Duigou, S. and Michel, B. (2010) RNA polymerase mutations that facilitate replication progression in the rep uvrD recF mutant lacking two accessory replicative helicases. *Mol. Microbiol.*, **77**, 324-336.
  48. Trautinger, B.W. and Lloyd, R.G. (2002) Modulation of DNA repair by mutations flanking the DNA channel through RNA polymerase. *EMBO J.*, **21**, 6944-6953.
  49. Nurse, P., Zavitz, K.H. and Marians, K.J. (1991) Inactivation of the *Escherichia coli* priA DNA replication protein induces the SOS response. *J. Bacteriol.*, **173**, 6686-6693.
  50. Mahdi, A.A., Briggs, G.S. and Lloyd, R.G. (2012) Modulation of DNA damage tolerance in *Escherichia coli* recG and ruv strains by mutations affecting PriB, the ribosome and RNA polymerase. *Mol. Microbiol.*, **86**, 675-691.
  51. Syeda, A.H., Hawkins, M. and McGlynn, P. (2014) Recombination and replication. *Cold Spring Harb. Perspect. Biol.*, **6**, a016550.
  52. Veaute, X., Delmas, S., Selva, M., Jeusset, J., Le Cam, E., Matic, I., Fabre, F. and Petit, M.A. (2005) UvrD helicase, unlike Rep helicase, dismantles RecA nucleoprotein filaments in *Escherichia coli*. *EMBO J.*, **24**, 180-189.
  53. Petit, M.A. and Ehrlich, D. (2002) Essential bacterial helicases that counteract the toxicity of recombination proteins. *EMBO J.*, **21**, 3137-3147.
  54. Lestini, R. and Michel, B. (2008) UvrD and UvrD252 counteract RecQ, RecJ, and RecFOR in a rep mutant of *Escherichia coli*. *J. Bacteriol.*, **190**, 5995-6001.
  55. Mahdi, A.A., Buckman, C., Harris, L. and Lloyd, R.G. (2006) Rep and PriA helicase activities prevent RecA from provoking unnecessary recombination during replication fork repair. *Genes Dev.*, **20**, 2135-2147.
  56. Ude, S., Lassak, J., Starosta, A.L., Kraxenberger, T., Wilson, D.N. and Jung, K. (2013) Translation elongation factor EF-P alleviates ribosome stalling at polyproline stretches. *Science*, **339**, 82-85.
  57. Li, H. and Durbin, R. (2009) Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics*, **25**, 1754-1760.
  58. Li, H., Handsaker, B., Wysoker, A., Fennell, T., Ruan, J., Homer, N., Marth, G., Abecasis, G., Durbin, R. and Genome Project Data Processing, S. (2009)

- The Sequence Alignment/Map format and SAMtools. *Bioinformatics*, **25**, 2078-2079.
59. Thorvaldsdottir, H., Robinson, J.T. and Mesirov, J.P. (2013) Integrative Genomics Viewer (IGV): high-performance genomics data visualization and exploration. *Brief. Bioinform.*, **14**, 178-192.
  60. Neidhardt, F.C., Bloch, P.L. and Smith, D.F. (1974) Culture medium for enterobacteria. *J. Bacteriol.*, **119**, 736-747.
  61. Low, B. (1973) Rapid mapping of conditional and auxotrophic mutations in *Escherichia coli* K-12. *J. Bacteriol.*, **113**, 798-812.
  62. Lloyd, R.G. and Buckman, C. (1991) Genetic analysis of the *recG* locus of *Escherichia coli* K-12 and of its role in recombination and DNA repair. *J. Bacteriol.*, **173**, 1004-1011.
  63. Theodore, A., Lewis, K. and Vulic, M. (2013) Tolerance of *Escherichia coli* to Fluoroquinolone Antibiotics Depends on Specific Components of the SOS Response Pathway. *Genetics*, **195**, 1265-1276.
  64. Hawkins, M., Atkinson, J. and McGlynn, P. (2016) *Escherichia coli* Chromosome Copy Number Measurement Using Flow Cytometry Analysis. *Methods Mol. Biol.*, **1431**, 151-159.
  65. Bernhardt, T.G. and de Boer, P.A. (2004) Screening for synthetic lethal mutants in *Escherichia coli* and identification of EnvC (YibP) as a periplasmic septal ring factor with murein hydrolase activity. *Mol. Microbiol.*, **52**, 1255-1269.
  66. McGlynn, P. and Lloyd, R.G. (2000) Modulation of RNA polymerase by (p)ppGpp reveals a RecG-dependent mechanism for replication fork progression. *Cell*, **101**, 35-45.
  67. Friedberg, E.C., Walker, G.C. and Siede, W. (2006) *DNA repair and mutagenesis*. 2nd ed. / Errol C. Friedberg ... [et al.]. ed. ASM Press, Washington, D.C.
  68. Magner, D.B., Blankschien, M.D., Lee, J.A., Pennington, J.M., Lupski, J.R. and Rosenberg, S.M. (2007) RecQ promotes toxic recombination in cells lacking recombination intermediate-removal proteins. *Mol. Cell*, **26**, 273-286.
  69. Sparkowski, J. and Das, A. (1990) The nucleotide sequence of *greA*, a suppressor gene that restores growth of an *Escherichia coli* RNA polymerase mutant at high temperature. *Nucleic Acids Res.*, **18**, 6443.
  70. Jones, C.N., Jones, C.I., Graham, W.D., Agris, P.F. and Spremulli, L.L. (2008) A disease-causing point mutation in human mitochondrial tRNA<sup>Met</sup> results in tRNA misfolding leading to defects in translational initiation and elongation. *The Journal of biological chemistry*, **283**, 34445-34456.
  71. Eiler, S., Dock-Bregeon, A., Moulinier, L., Thierry, J.C. and Moras, D. (1999) Synthesis of aspartyl-tRNA(Asp) in *Escherichia coli*--a snapshot of the second step. *EMBO J.*, **18**, 6532-6541.
  72. Jovine, L., Djordjevic, S. and Rhodes, D. (2000) The crystal structure of yeast phenylalanine tRNA at 2.0 Å resolution: cleavage by Mg(2+) in 15-year old crystals. *J. Mol. Biol.*, **301**, 401-414.
  73. Sharples, G.J. and Lloyd, R.G. (1991) Location of a mutation in the aspartyl-tRNA synthetase gene of *Escherichia coli* K12. *Mutat. Res.*, **264**, 93-96.
  74. Martin, F., Sharples, G.J., Lloyd, R.G., Eiler, S., Moras, D., Gangloff, J. and Eriani, G. (1997) Characterization of a thermosensitive *Escherichia coli* aspartyl-tRNA synthetase mutant. *J. Bacteriol.*, **179**, 3691-3696.
  75. Doerfel, L.K., Wohlgemuth, I., Kothe, C., Peske, F., Urlaub, H. and Rodnina, M.V. (2013) EF-P is essential for rapid synthesis of proteins containing consecutive proline residues. *Science*, **339**, 85-88.
  76. Yanagisawa, T., Sumida, T., Ishii, R., Takemoto, C. and Yokoyama, S. (2010) A paralog of lysyl-tRNA synthetase aminoacylates a conserved lysine residue in translation elongation factor P. *Nat. Struct. Mol. Biol.*, **17**, 1136-1143.



77. Park, J.H., Johansson, H.E., Aoki, H., Huang, B.X., Kim, H.Y., Ganoza, M.C. and Park, M.H. (2012) Post-translational modification by beta-lysylation is required for activity of *Escherichia coli* elongation factor P (EF-P). *J. Biol. Chem.*, **287**, 2579-2590.
78. Navarre, W.W., Zou, S.B., Roy, H., Xie, J.L., Savchenko, A., Singer, A., Edvokimova, E., Prost, L.R., Kumar, R., Ibba, M. *et al.* (2010) PoxA, YjeK, and elongation factor P coordinately modulate virulence and drug resistance in *Salmonella enterica*. *Mol. Cell*, **39**, 209-221.
79. Cashel, M. (1994) In Adolph, K. W. (ed.), *Methods in Molecular Genetics*. Academic Press, New York, N. Y., Vol. 3, pp. 341-356.
80. Ryals, J., Little, R. and Bremer, H. (1982) Control of rRNA and tRNA syntheses in *Escherichia coli* by guanosine tetraphosphate. *J. Bacteriol.*, **151**, 1261-1268.
81. Laffler, T. and Gallant, J.A. (1974) Stringent control of protein synthesis in *E. coli*. *Cell*, **3**, 47-49.
82. Nguyen, D., Joshi-Datar, A., Lepine, F., Bauerle, E., Olakanmi, O., Beer, K., McKay, G., Siehnel, R., Schafhauser, J., Wang, Y. *et al.* (2011) Active starvation responses mediate antibiotic tolerance in biofilms and nutrient-limited bacteria. *Science*, **334**, 982-986.
83. Gaillard, H. and Aguilera, A. (2016) Transcription as a Threat to Genome Integrity. *Annu. Rev. Biochem.*
84. Peters, J.M., Vangeloff, A.D. and Landick, R. (2011) Bacterial transcription terminators: the RNA 3'-end chronicles. *J. Mol. Biol.*, **412**, 793-813.
85. Fassler, J.S., Tessman, I. and Tessman, E.S. (1985) Lethality of the double mutations *rho rep* and *rho ssb* in *Escherichia coli*. *J. Bacteriol.*, **161**, 609-614.
86. Harinarayanan, R. and Gowrishankar, J. (2003) Host factor titration by chromosomal R-loops as a mechanism for runaway plasmid replication in transcription termination-defective mutants of *Escherichia coli*. *J. Mol. Biol.*, **332**, 31-46.
87. Peil, L., Starosta, A.L., Lassak, J., Atkinson, G.C., Virumae, K., Spitzer, M., Tenson, T., Jung, K., Remme, J. and Wilson, D.N. (2013) Distinct XPPX sequence motifs induce ribosome stalling, which is rescued by the translation elongation factor EF-P. *Proc. Natl. Acad. Sci. U S A*, **110**, 15265-15270.
88. Roberts, J.W., Shankar, S. and Filter, J.J. (2008) RNA polymerase elongation factors. *Annu. Rev. Microbiol.*, **62**, 211-233.
89. Starosta, A.L., Lassak, J., Jung, K. and Wilson, D.N. (2014) The bacterial translation stress response. *FEMS Microbiol. Rev.*, **38**, 1172-1201.

## Figure Legends

**Figure 1.** A mutation in an aspartyl tRNA gene suppresses the need for accessory replicative helicases and for anti-backtracking factors.

(A) Retention or loss of pRC7*uvrD* (pAM407) from strains without or with  $\Delta rep \Delta uvrD$  deletions as judged by blue/white colony colour on LB plates containing X-gal and IPTG. Fractions of white colonies are indicated below each image with actual numbers of white versus total colonies counted in parentheses.

(B) DNA content of the indicated strains as monitored by flow cytometry under run out conditions in LB. The number of chromosome equivalents per cell is shown below.

(C) The viability of *greA*<sup>+</sup> *greB*<sup>+</sup> versus  $\Delta greA \Delta greB$  cells without and with *aspT*[t8c] as monitored by serial dilutions of liquid cultures grown at 30°C and plated subsequently on LB agar at 30°C and 42°C.

**Figure 2.** The impact of *aspT*[t8c] on growth and its relevance to  $\Delta rep \Delta uvrD$  inviability.

(A) Growth of (i) *aspT*<sup>+</sup> *efp*<sup>+</sup> (TB28), (ii) *aspT*[t8c] *efp*<sup>+</sup> (KM231) and (iii) *aspT*<sup>+</sup>  $\Delta efp$  (MH299) in LB at 37°C as monitored by absorbance at 600 nm.

(B) Assessment of the ability of pRC7*uvrD* (pAM407) to be lost from  $\Delta rep \Delta uvrD$  cells by reducing growth rates via culturing at 37°C and 25°C for the indicated times on defined rich medium containing glycerol as a carbon source.

**Figure 3.** A mutation in aspartyl tRNA synthetase suppresses  $\Delta rep \Delta uvrD$  lethality.

(A) The indicated strains were grown overnight in high salt medium at 30°C and then serial dilutions plated onto low and high salt plates containing 100 µg ml<sup>-1</sup> ampicillin and incubated at either 30°C or 42°C.

(B) Suppression of  $\Delta rep \Delta uvrD$  lethality by *aspS*<sup>P555S</sup> on rich medium was analysed by monitoring retention or loss of pRC7*uvrD* (pAM407) from the indicated strains at 30°C on either low or high salt LB medium.

**Figure 4.** Ribosomal pausing decreases the requirement for accessory helicase activity.

Retention or loss of pRC7*rep* (pAM403) was monitored at 37°C on LB X-gal IPTG plates for the indicated strains.

**Figure 5.** (p)ppGpp synthesis is needed for suppression of  $\Delta rep \Delta uvrD$  lethality by *aspT*[t8c] and  $\Delta efp$ .

(A) Flow cytometric detection of *in vivo* levels of RpoS-mCherry fluorescence in the indicated strains. All strains contain the *rpoS-mCherry* fusion with the exception of (i) MG1655.

(B) Survival after challenge with ciprofloxacin. The strains are (i) TB28, (ii) KM241, (iii) N5777, (iv) KM231 and (v) MH372.

(C) Retention and loss of pRC7*uvrD* (pAM407) on LB X-gal IPTG agar in *relA*<sup>+</sup> and  $\Delta relA$  strains.

**Figure 6.**  $\Delta efp$  but not *aspT*[t8c] can bypass the need for wild type Rho activity.

(A) and (B) The indicated strains were grown in liquid culture in the absence of bicyclomycin and their ability to continue to divide with reduced Rho activity was assessed after serial dilution onto plates without and with 25 µg ml<sup>-1</sup> bicyclomycin.

(C) Loss of pRC7*rep* (pAM403) on LB X-gal IPTG agar in *rho*<sup>+</sup> (i, iii, v) and *rho*[A243E] (ii, iv, vi) strains.

**Figure 7.** The ability of  $\Delta efp$  to bypass the requirement for wild type Rho activity is dependent on (p)ppGpp synthesis.

(A) and (B) Strains were grown in the absence of bicyclomycin and then serial

dilutions were plated onto LB agar without and with 25  $\mu\text{g ml}^{-1}$  bicyclomycin.

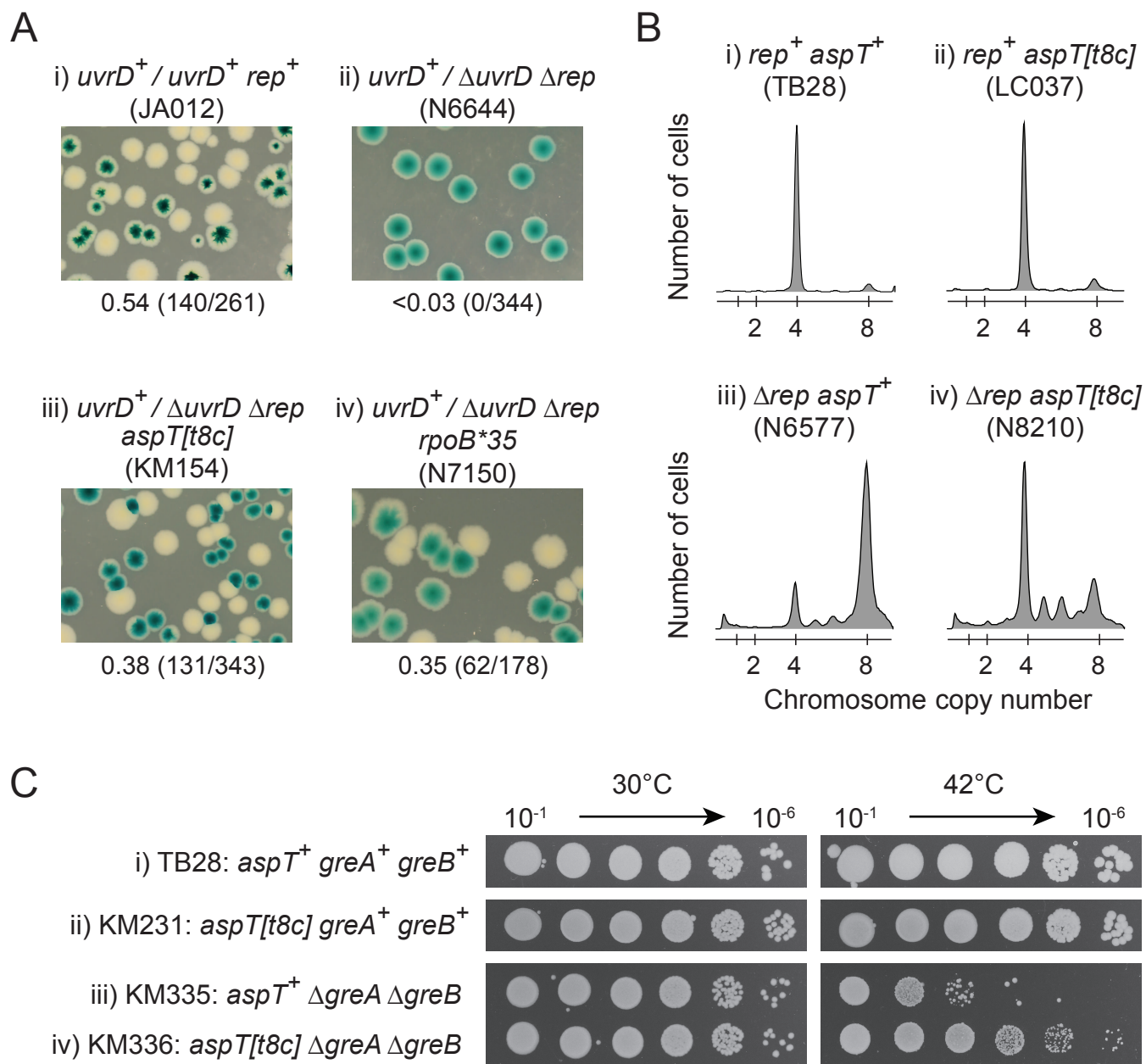


Figure 1

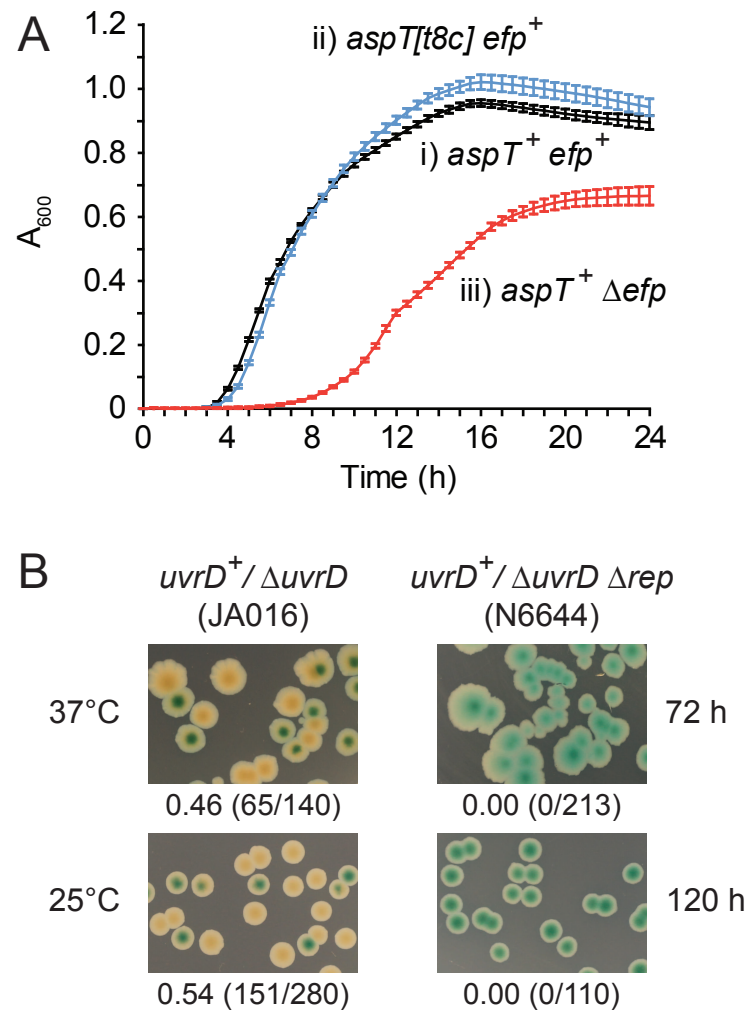


Figure 2

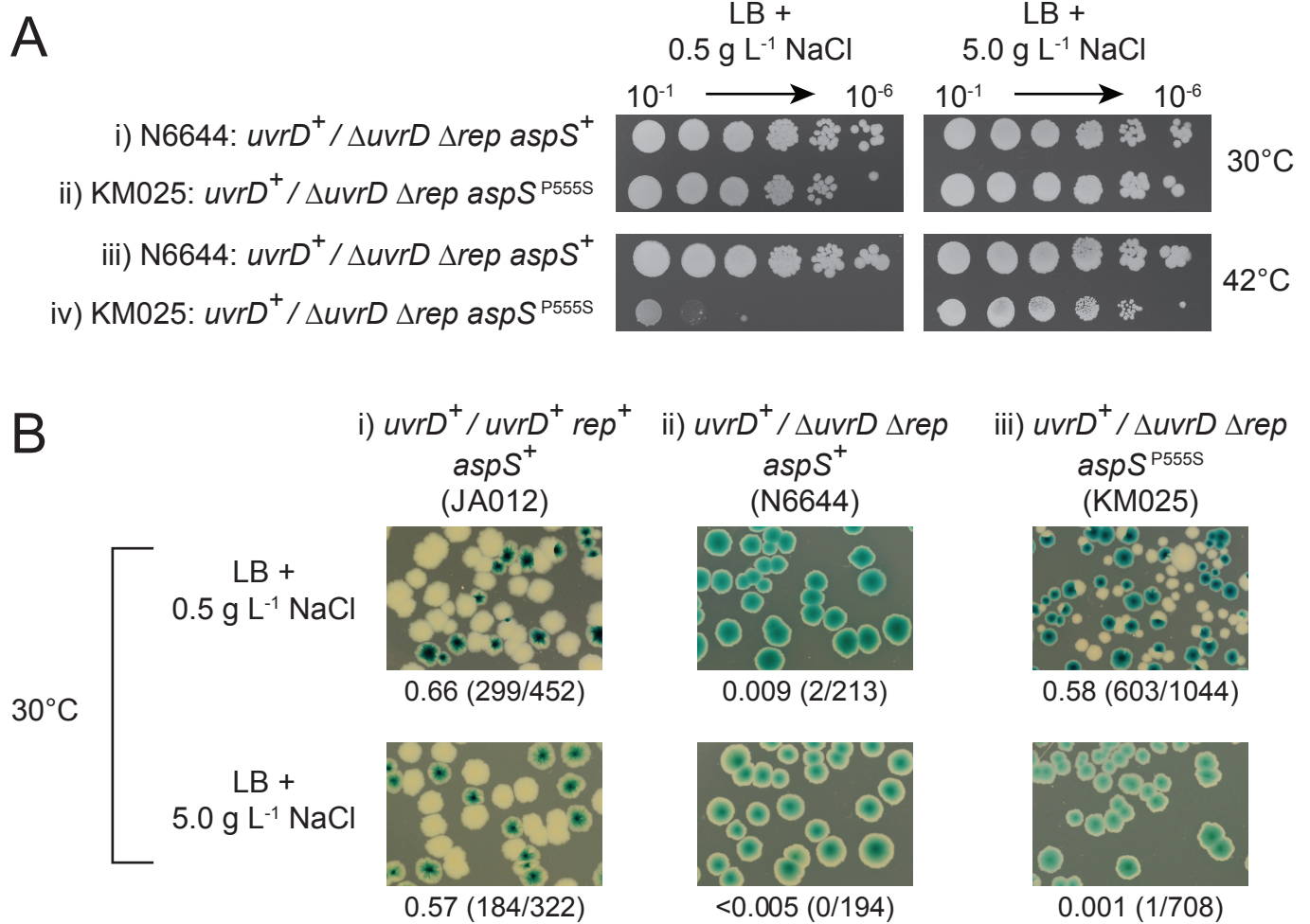


Figure 3

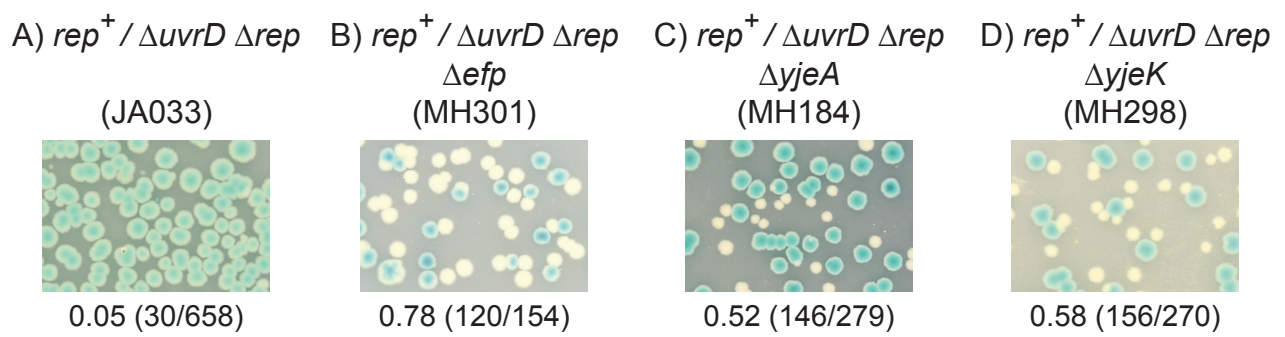


Figure 4

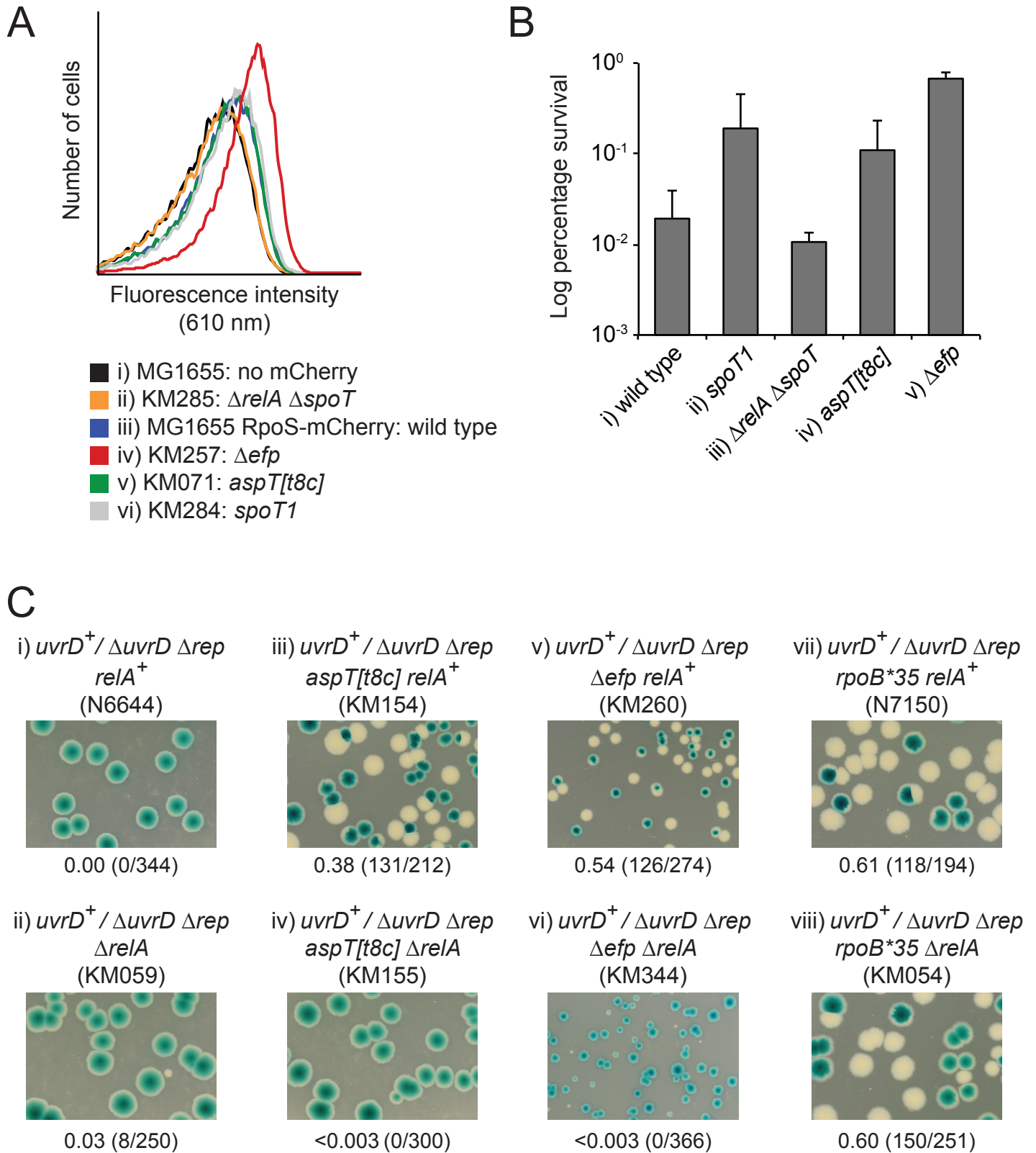


Figure 5



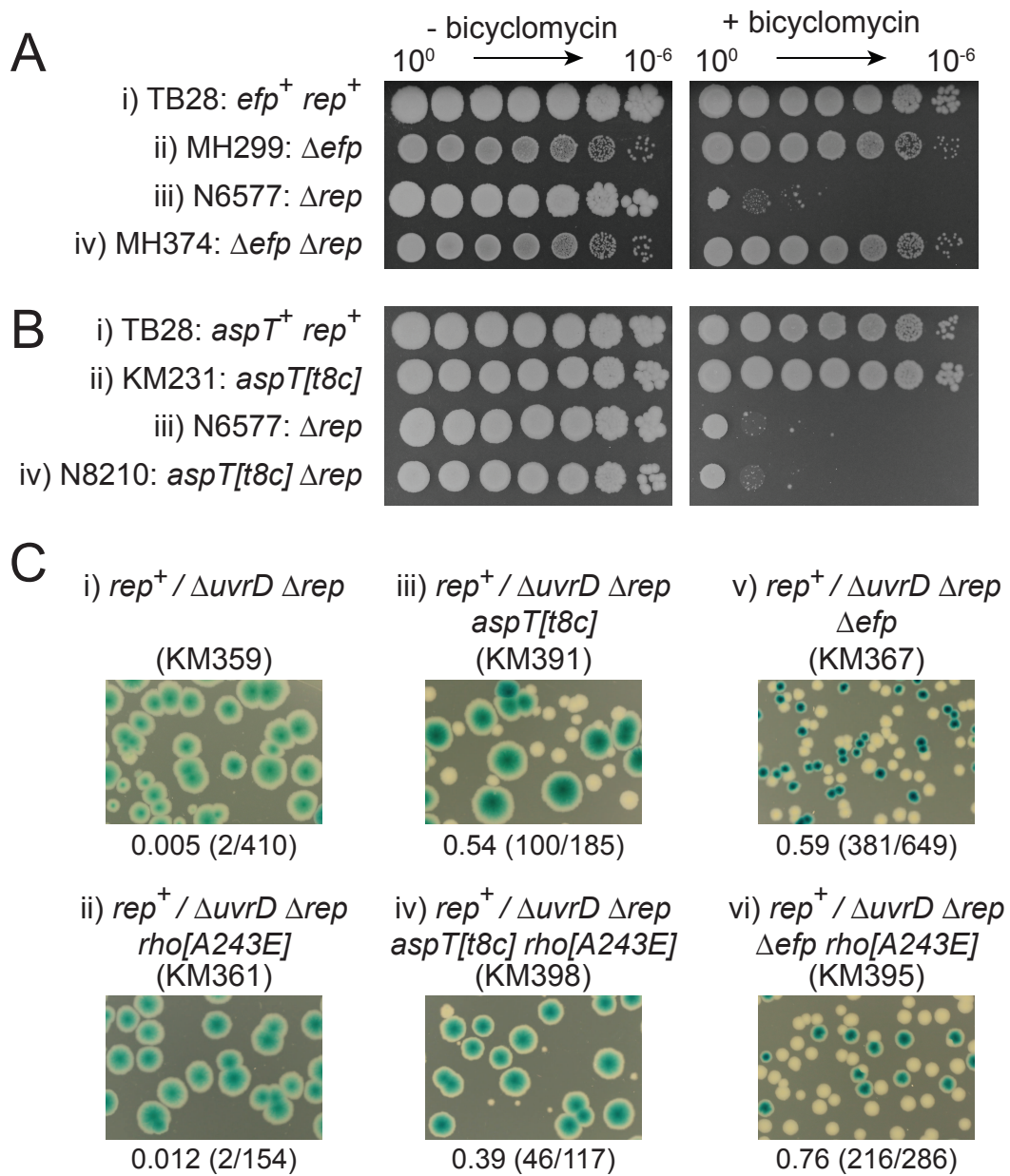


Figure 6

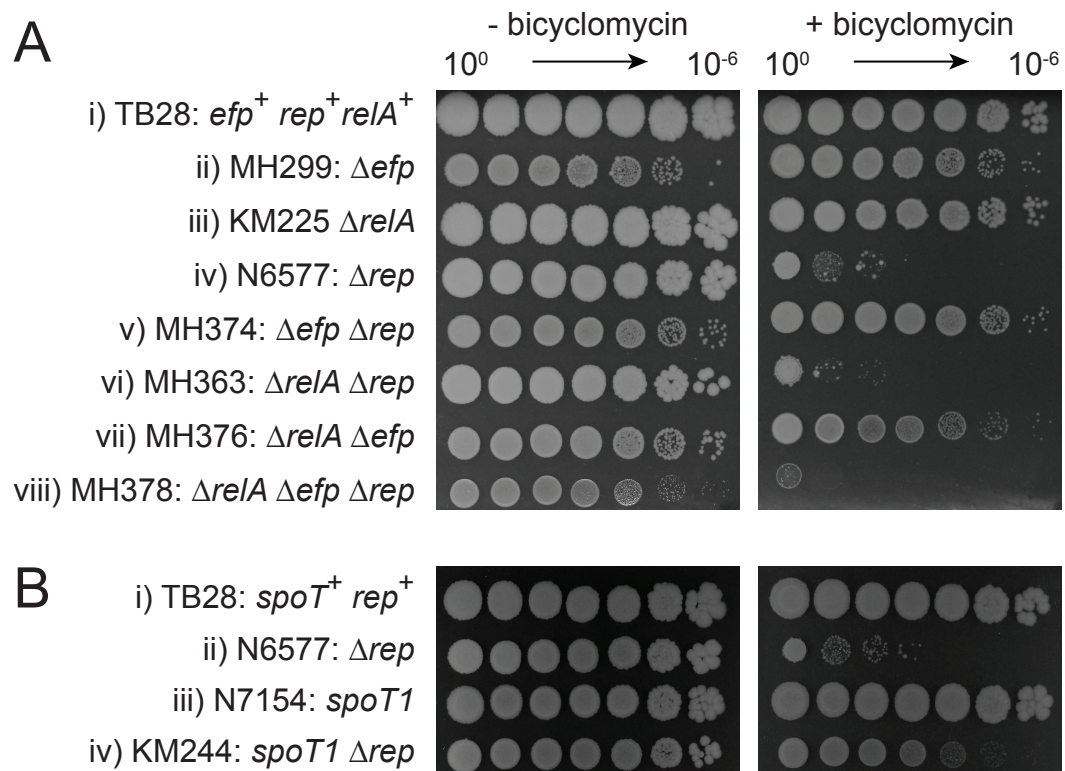
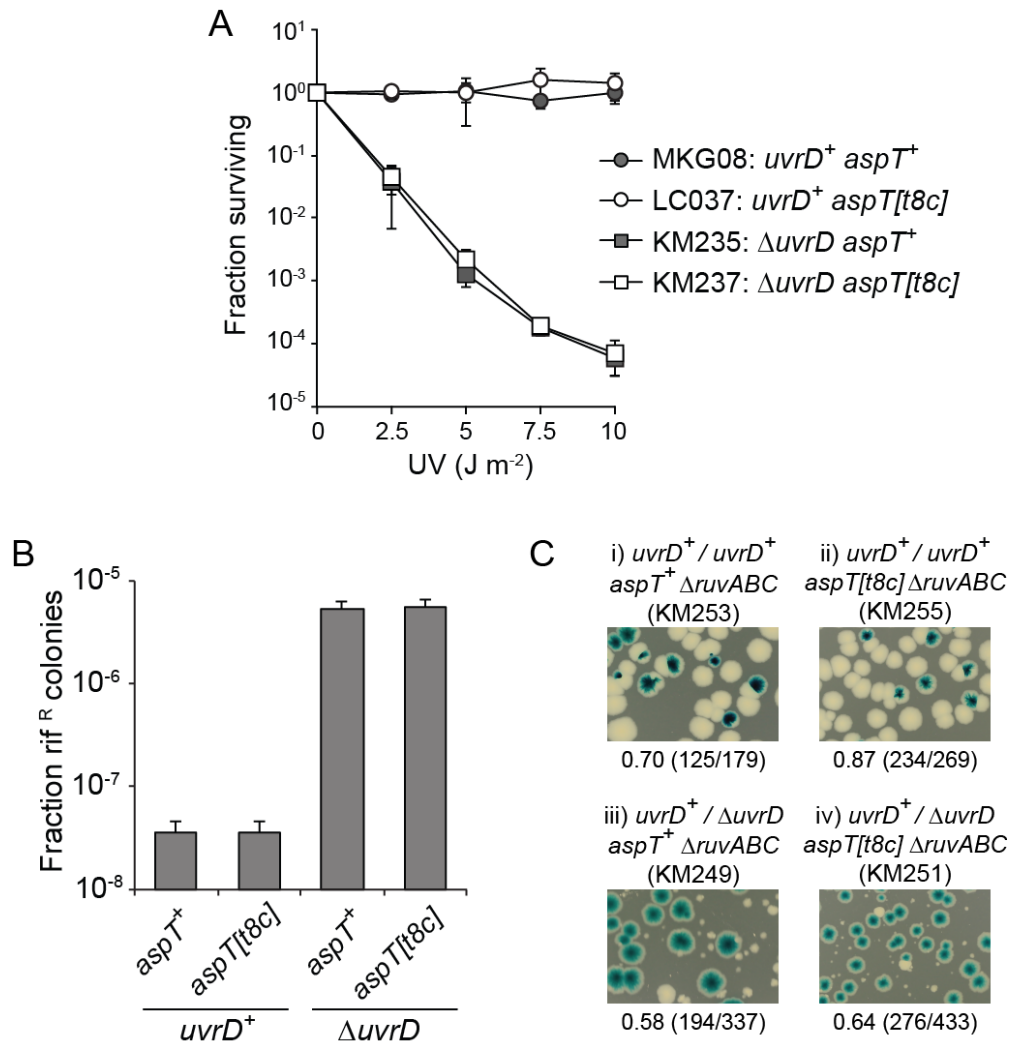


Figure 7

## Supplementary Information

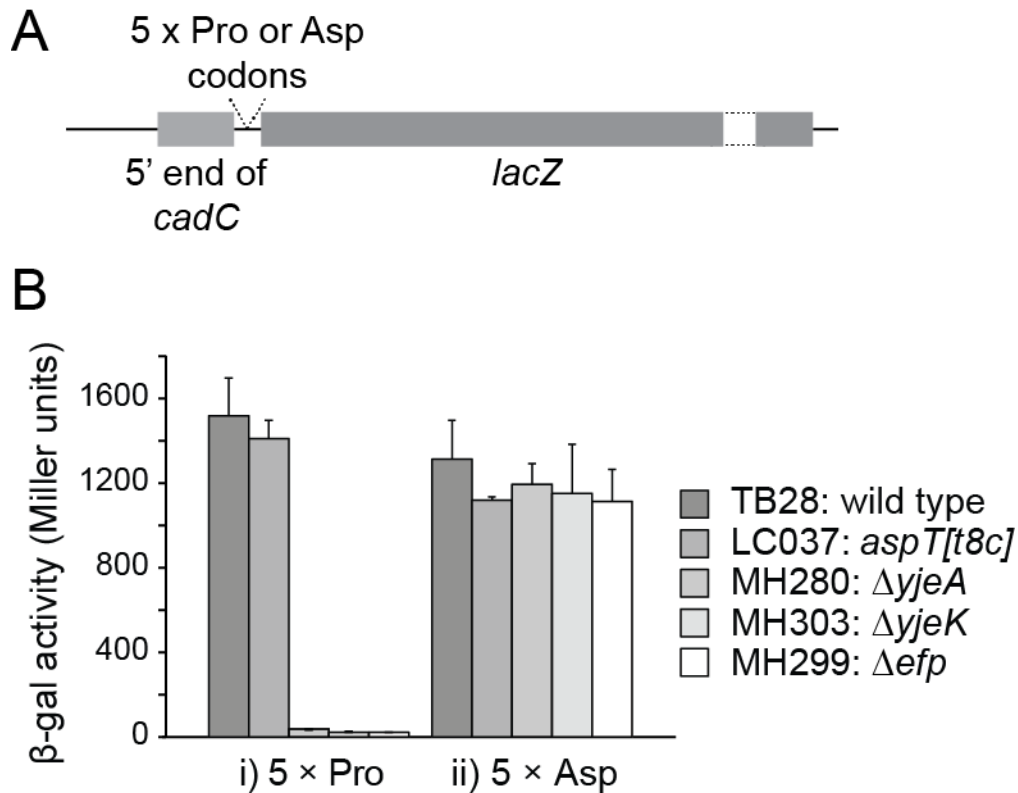


**Supplementary Figure 1.** *aspT*[*t8c*] does not suppress defects in nucleotide excision repair, mismatch repair or control of recombination in  $\Delta$ *uvrD* cells.

(A) *Nucleotide excision repair*. The ability of the indicated strains to survive exposure to DNA damage was assessed at increasing doses of 254 nm UV light.  $\Delta$ *uvrD* cells were sensitive to UV light as compared with *uvrD*<sup>+</sup> and this sensitivity was not suppressed by *aspT*[*t8c*] (compare KM235 and 237).

(B) *Mismatch repair*. The accumulation of rifampicin-resistant spontaneous mutations upon growth of a single colony to stationary phase in liquid culture was used as a readout of mismatch repair. The strains were those used in panel (A).  $\Delta$ *uvrD* cells gave rise to more rifampicin resistant colonies as compared with *uvrD*<sup>+</sup> but this defect in mismatch repair was not suppressed by *aspT*[*t8c*].

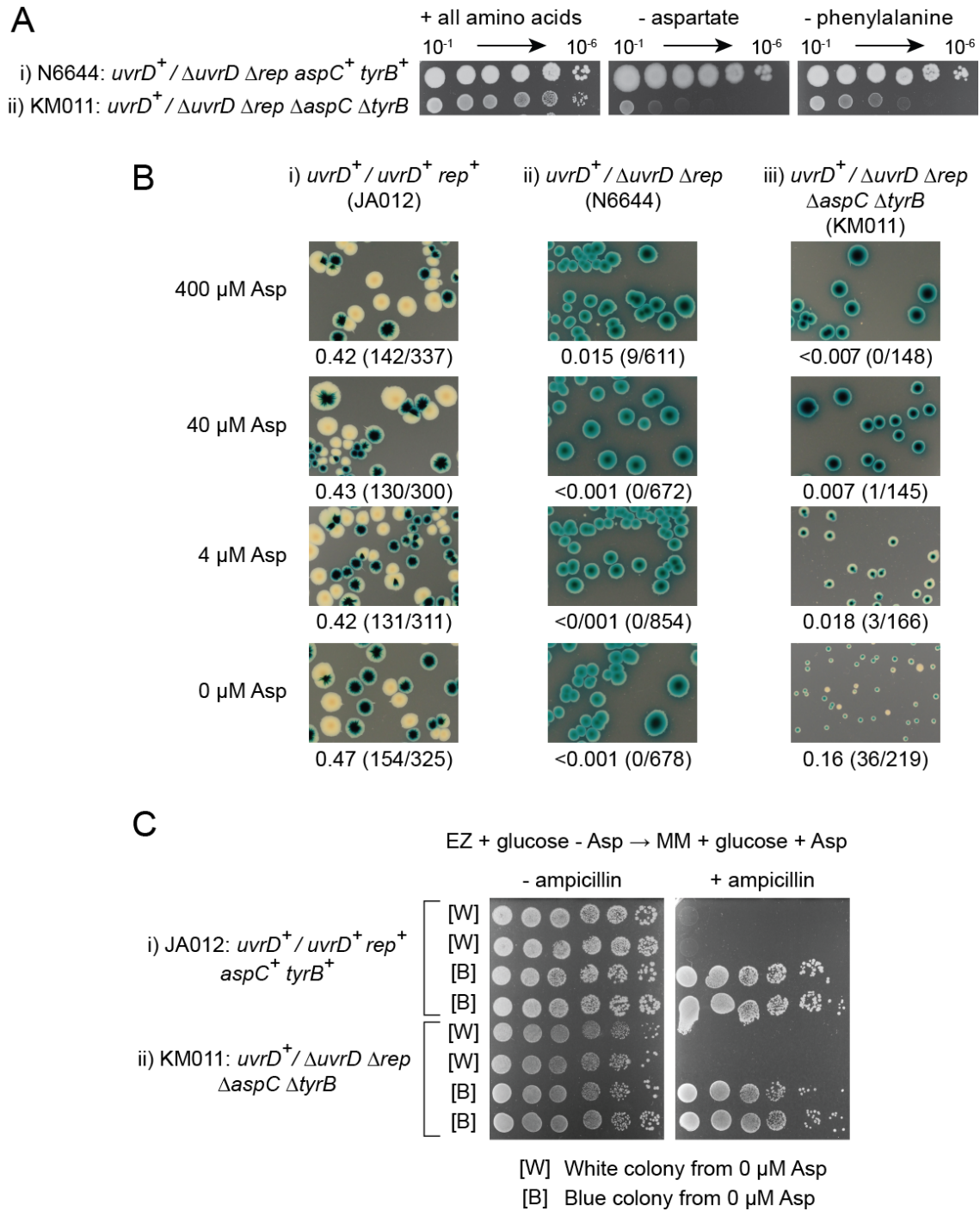
(C) *Control of recombination*. UvrD modulates levels of homologous recombination by displacing RecA from DNA (1). When RecA-directed strand exchange does proceed then RuvABC resolves any Holliday junctions formed thus facilitating chromosome segregation by removing interchromosomal Holliday junctions (2). Thus UvrD inhibits formation of interchromosomal Holliday junctions whilst RuvABC resolves such junctions when they do form. Efficient chromosome segregation requires either UvrD or RuvABC in *recA*<sup>+</sup> cells, evinced by the very low viability of  $\Delta$ *uvrD*  $\Delta$ *ruvABC* cells (2). Thus pRC7*uvrD* can be lost from *uvrD*<sup>+</sup>  $\Delta$ *ruvABC* cells on LB agar at high frequency with no significant impact on plasmidless white colony size whereas plasmidless  $\Delta$ *uvrD*  $\Delta$ *ruvABC* colonies are very small, indicative of a severe viability problem (compare i with iii). This viability problem was not suppressed by *aspT*[*t8c*] (compare iii and iv).



**Supplementary Figure 2.** *aspT[t8c]* does not cause significant pausing of ribosomes at aspartate codons.

(A) Schematic of the gene fusion cassette used to assess the relative impact of codons on efficiency of translation (3). The first 30 codons of *cadC* are fused in frame with *lacZ* via a linker sequence that encodes five consecutive aspartate or proline codons.  $\beta$ -galactosidase assays are then used with transformed *E. coli* cells to determine the impact of the repeated aspartate and proline codons on LacZ levels, providing a readout of translational efficiency.

(B) (i) YjeA, YjeK and EF-P are all needed for efficient translation of polyproline sequences and, as expected, levels of translation of the *lacZ* fusion protein from a plasmid containing five proline codons (p3LC-TL30-5P) (3) are inhibited when any one of these factors is absent as compared with a wild type strain. (ii) In contrast, the *aspT[t8c]* mutation does not result in significant inhibition of translation of *lacZ* from the plasmid encoding five tandem aspartate codons (p3LC-TL30-5D) as indicated by the similar levels of  $\beta$ -galactosidase activity in wild type and *aspT[t8c]* strains.



**Supplementary Figure 3.** Restriction of aspartate availability suppresses  $\Delta$ *rep*  $\Delta$ *uvrD* lethality.

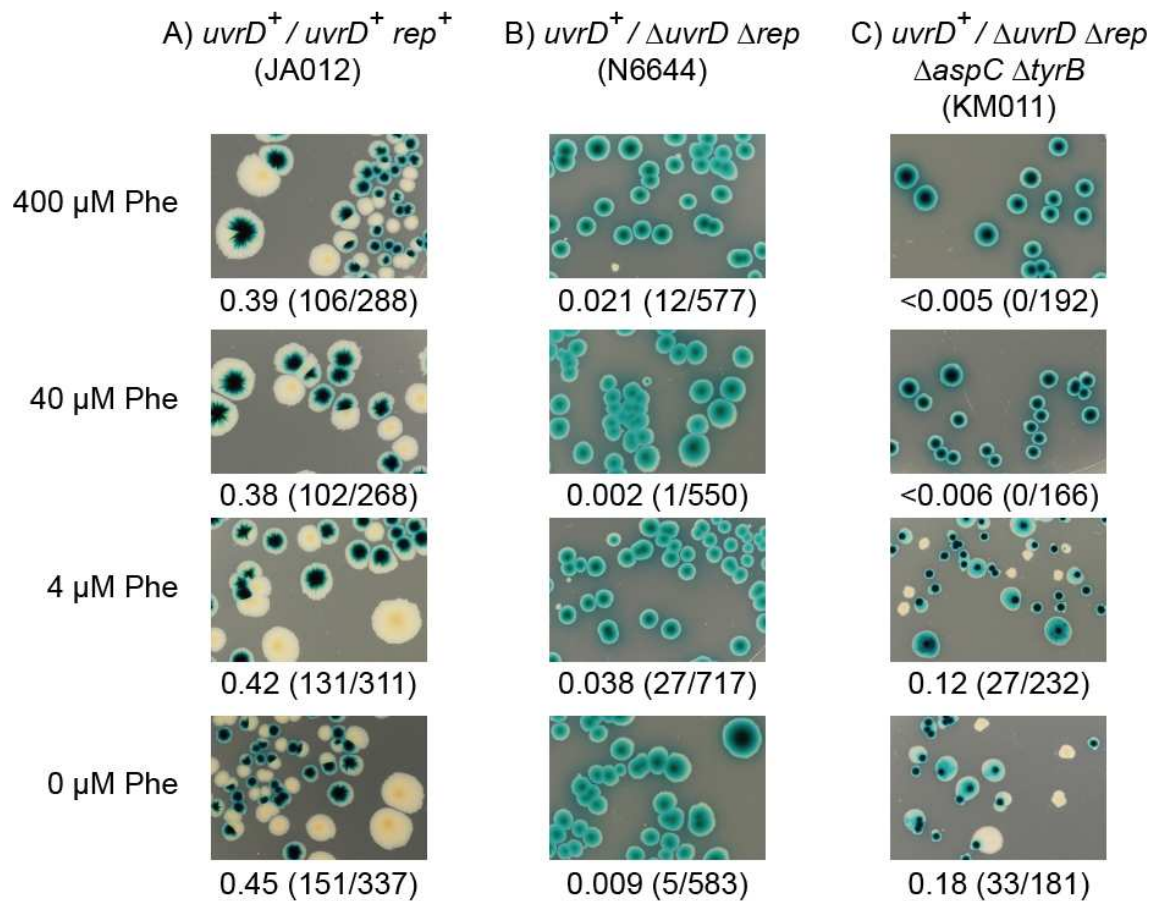
(A) Aspartate auxotrophy requires mutations in both aspartate aminotransferase and aromatic amino acid aminotransferase, encoded by *aspC* and *tyrB* respectively, since each can catalyse the transamination of oxaloacetate from glutamate to form aspartate (4,5). Both these aminotransferases can also catalyse the final step in phenylalanine biosynthesis but *aspC tyrB* strains still synthesise phenylalanine since the branched chain amino acid aminotransferase encoded by *ilvE* can catalyse this reaction to a limited extent (4,6). We introduced both *aspC* and *tyrB* deletions into pRC7*uvrD*/ $\Delta$ *rep*  $\Delta$ *uvrD*. This strain (ii) could grow on defined rich medium when all amino acids were provided, although colony sizes were reduced. Absence of aspartate or phenylalanine exacerbated this growth defect severely but weak growth was still observable. Restricted growth was expected in the absence of phenylalanine via the *ilvE*-encoded branched chain amino acid aminotransferase (4,6). However, the

limited growth in the absence of added aspartate suggests that trace amounts of aspartate were present in preparations of the other amino acids present in the defined medium.

(B) Retention or loss of pRC7*uvrD* was monitored for the indicated strains on defined rich medium with decreasing concentrations of added aspartate. Absence of added aspartate had no significant impact on colony sizes or on frequency of loss of pRC7*uvrD* for either (i) JA012 or (ii) N6644, as expected since both strains retain the *aspC* and *tyrB* genes but colony sizes for (iii) KM011 decreased with decreasing aspartate concentration. Very small KM011 colonies could still form in the absence of added aspartate, consonant with the very restricted growth seen in (Aii), and some of these colonies were white indicating loss of pRC7*uvrD*. Limiting the availability of aspartate therefore suppresses  $\Delta rep \Delta uvrD$  lethality.

(C) Loss of pRC7*uvrD* from KM011 in the absence of added aspartate (see Biii) was confirmed by using ampicillin resistance as a marker for the presence or absence of pRC7*uvrD* which encodes  $\beta$  lactamase. Two white [W] and two blue [B] colonies of KM011 and JA012 from the 0  $\mu$ M aspartate plates in (B) were resuspended in 100  $\mu$ L 56/2 salts solution, serially diluted in the same salts solution and 5  $\mu$ L of the  $10^0$ - $10^{-5}$  dilutions spotted onto minimal medium plates containing glucose and all amino acids without and with ampicillin. All dilutions of resuspended blue colonies gave colonies on plates regardless of the presence of ampicillin indicating that these colonies retained pRC7*uvrD* as expected. In contrast, all dilutions of resuspended white colonies gave colonies only in the absence of ampicillin. We conclude that the small white colonies isolated from KM011 on 0  $\mu$ M aspartate plates in (B) had indeed lost pRC7*uvrD*, confirming suppression of  $\Delta rep \Delta uvrD$  lethality by restricting aspartate availability.





**Supplementary Figure 4.** Suppression of  $\Delta$ *rep*  $\Delta$ *uvrD* lethality by restriction of amino acid availability is not specific to aspartate metabolism.

The ability of a  $\Delta$ *rep*  $\Delta$ *uvrD*  $\Delta$ *aspC*  $\Delta$ *tyrB* strain, KM011, to lose pRC7*uvrD* at decreasing phenylalanine concentrations on defined rich medium was assessed. Colony morphology was altered at lower added phenylalanine concentrations but it was also clear that some of these colonies were white, indicating loss of pRC7*uvrD* (compare B and C at 4 and 0  $\mu$ M phenylalanine). Restriction of phenylalanine availability therefore reduced the need for accessory replicative helicase activity in a manner similar to the suppression seen upon aspartate restriction (Supplementary Figure 3).

## References

1. Veaute, X., Delmas, S., Selva, M., Jeusset, J., Le Cam, E., Matic, I., Fabre, F. and Petit, M.A. (2005) UvrD helicase, unlike Rep helicase, dismantles RecA nucleoprotein filaments in *Escherichia coli*. *EMBO J.*, **24**, 180-189.
2. Magner, D.B., Blankschien, M.D., Lee, J.A., Pennington, J.M., Lupski, J.R. and Rosenberg, S.M. (2007) RecQ promotes toxic recombination in cells lacking recombination intermediate-removal proteins. *Mol. Cell*, **26**, 273-286.
3. Ude, S., Lassak, J., Starosta, A.L., Kraxenberger, T., Wilson, D.N. and Jung, K. (2013) Translation elongation factor EF-P alleviates ribosome stalling at polyproline stretches. *Science*, **339**, 82-85.
4. Gelfand, D.H. and Steinberg, R.A. (1977) *Escherichia coli* mutants deficient in the aspartate and aromatic amino acid aminotransferases. *J. Bacteriol.*, **130**, 429-440.
5. Fotheringham, I.G., Dacey, S.A., Taylor, P.P., Smith, T.J., Hunter, M.G., Finlay, M.E., Primrose, S.B., Parker, D.M. and Edwards, R.M. (1986) The cloning and sequence analysis of the *aspC* and *tyrB* genes from *Escherichia coli* K12. Comparison of the primary structures of the aspartate aminotransferase and aromatic aminotransferase of *E. coli* with those of the pig aspartate aminotransferase isoenzymes. *Biochem. J.*, **234**, 593-604.
6. Lee-Peng, F.C., Hermodson, M.A. and Kohlhaw, G.B. (1979) Transaminase B from *Escherichia coli*: quaternary structure, amino-terminal sequence, substrate specificity, and absence of a separate valine-alpha-ketoglutarate activity. *J. Bacteriol.*, **139**, 339-345.



**Supplementary Table 1. *Escherichia coli* K12 strains.**

**A) MG1655 derivatives**

MG1655	F <sup>-</sup> <i>rph-1</i>	(1)
GJ6520	<i>lacI lacZU<sub>118</sub> trpR55 trpE9777 rho[A243E]</i> <i>Δ(yefM-yoeB)::Cm</i>	(2)
JA012	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i>	TB28 x pAM407 to Amp <sup>r</sup>
JA016	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr</i>	N6632 x pAM407 to Amp <sup>r</sup>
JA033	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat</i>	Plasmid-free segregant of N6644 formed on minimal medium subsequently transformed with pAM403 to Amp <sup>r</sup>
KM001	<i>ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr</i> <i>ΔaspC745::&lt;Kan&gt;</i>	P1.JW0911 x N6632 to Km <sup>r</sup>
KM003	<i>ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr ΔaspC745::&lt;&gt;</i>	KM001 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM005	<i>ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr ΔaspC745::&lt;&gt;</i> <i>ΔtyrB747::&lt;kan&gt;</i>	P1.JW4014 x KM003 to Km <sup>r</sup>
KM007	<i>ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr ΔaspC745::&lt;&gt;</i> <i>ΔtyrB747::&lt;&gt;</i>	KM005 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM009	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr ΔaspC745::&lt;&gt; ΔtyrB747::&lt;&gt;</i>	pAM407 x KM007 to Amp <sup>r</sup>
KM011	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat ΔaspC745::&lt;&gt;</i> <i>ΔtyrB747::&lt;&gt;</i>	P1.N6577x KM009 to Cm <sup>r</sup>
KM021	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr tls-1 eda-51::Tn10</i>	P1.CS89 x N6632 to Tm <sup>r</sup>
KM025	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat tls-1 eda-51::Tn10</i>	P1.N6577 x KM021 to Cm <sup>r</sup>
KM050	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr ΔrelA782::kan</i>	JA016 x P1.JW2755 to Km <sup>r</sup>
KM054	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>rpoB*35 ΔuvrD::dhfr Δrep::cat</i> <i>ΔrelA782::kan</i>	N7150 x P1.JW2755 to Km <sup>r</sup>
KM059	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat ΔrelA782::kan</i>	N6644 x P1.JW2755 to Km <sup>r</sup>
KM071	<i>rpoS-mCherry::&lt;&gt; rep<sup>+</sup>&lt;kan&gt; aspT[t8c]</i>	MG1655 RpoS-Mcherry x P1.LC037 to Km <sup>r</sup>
KM154	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat aspT[t8c]</i>	JA016 x P1.PM647 to Cm <sup>r</sup> . <i>aspT[t8c]</i> allele confirmed by sequencing
KM155	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat aspT[t8c]</i> <i>ΔrelA782::kan</i>	KM050 x P1.N7182 to Cm <sup>r</sup>
KM189	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr tls-1 Δeda775::kan</i>	KM021 x P1.JW1839 to Km <sup>r</sup> and temperature-

KM225	$\Delta lacIZYA::<> \Delta relA782::kan$	sensitive growth.
KM230	$lacI lacZU_{118} trpR55 trpE9777 rho[A243E]$ $\Delta(yefM-yoeB)::Cm \Delta rep729::kan$	TB28 x P1.JW2755 to Km <sup>r</sup> $\Delta rep729::kan$ integration into GJ6520 using pKD46 (4)
KM231	$\Delta lacIZYA::<> rep^+ <> aspT[t8c]$	LC037 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM235	$\Delta lacIZYA::<> \Delta uvrD::dhfr rep^+ <kan>$	N6632 x P1.MKG08 to Km <sup>r</sup>
KM237	$\Delta lacIZYA::<> \Delta uvrD::dhfr rep^+ <kan>$ $aspT[t8c]$	N6632 x P1.LC037 to Km <sup>r</sup>
KM239	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $\Delta uvrD::dhfr rep^+ <kan>$	KM235 x pAM407 to Amp <sup>r</sup>
KM240	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $\Delta uvrD::dhfr rep^+ <kan> aspT[t8c]$	KM237 x pAM407 to Amp <sup>r</sup>
KM241	$\Delta lacIZYA::<> spoT1$	N7154 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM244	$\Delta lacIZYA::<> \Delta rep::cat spoT1$	PM567 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM245	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<> rep^+$ $<kan>$	MKG08 x pAM407 to Amp <sup>r</sup>
KM246	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $rep^+ <kan> aspT[t8c]$	LC037 x pAM407 to Amp <sup>r</sup>
KM247	$\Delta lacIZYA::<> spoT1 rpoS-$ $mCherry::<kan>$	KM241 x P1. MG1655 RpoS-Mcherry Kan to Km <sup>r</sup>
KM249	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $\Delta uvrD::dhfr rep^+ <kan> \Delta ruvABC::cat$	KM239 x P1.N6268 to Cm <sup>r</sup>
KM251	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $\Delta uvrD::dhfr rep^+ <kan> aspT[t8c]$ $\Delta ruvABC::cat$	KM240 x P1.N6268 to Cm <sup>r</sup>
KM253	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<> rep^+$ $<kan> \Delta ruvABC::cat$	KM245 x P1.N6268 to Cm <sup>r</sup>
KM255	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $rep^+ <kan> aspT[t8c] \Delta ruvABC::cat$	KM246 x P1.N6268 to Cm <sup>r</sup>
KM257	$rpoS-mCherry::<> \Delta efp772::kan$	MG1655 RpoS-Mcherry x P1.JW4107 to Km <sup>r</sup>
KM260	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $\Delta uvrD::dhfr \Delta rep::cat \Delta efp772::<>$	KM280 x P1.N6644 to Km <sup>r</sup>
KM268	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $\Delta uvrD::dhfr \Delta efp772::kan$	JA016 x P1.JW4107 to Km <sup>r</sup>
KM269	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $rpoB^*35 \Delta uvrD::dhfr \Delta rep729::kan$	N7150 x P1.JW5604 to Km <sup>r</sup>
KM271	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$ $rpoB^*35 \Delta uvrD::dhfr \Delta rep729::kan$ $rho[A243E]$	N7150 x P1.KM230 to Km <sup>r</sup> and then screening for the mutant <i>rho</i> allele by sequencing
KM273	pAM407 ( $lac^+ uvrD^+$ ) / $\Delta lacIZYA::<>$	N6644 x P1.KM269 to Km <sup>r</sup>

KM275	<i>ΔuvrD::dhfr Δrep729::kan</i> pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>Δefp772::&lt;&gt;</i>	MH372 x pAM407 to Amp <sup>r</sup>
KM277	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan Δefp772::&lt;&gt;</i>	KM275 x P1.KM269 to Km <sup>r</sup> then screened for Tm <sup>r</sup>
KM280	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δefp772::&lt;&gt;</i>	Plasmid-free segregant of KM268 formed on LB subsequently transformed with pCP20 (3) to Amp <sup>r</sup> . Plasmid-free Km <sup>s</sup> segregant then identified after growth on LB at 42°C and then retransformed with pAM407 to Amp <sup>r</sup> . N6644 x P1.KM271 to Km <sup>r</sup>
KM281	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan rho[A243E]</i>	
KM284	<i>ΔlacIZYA::&lt;&gt; spoT1 rpoS-mCherry::&lt;&gt;</i>	KM247 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM285	<i>rpoS-mCherry::&lt;&gt; ΔrelA251::kan</i> <i>ΔspoT207::cat</i>	KM287 x P1.N5777 to Cm <sup>r</sup>
KM287	<i>rpoS-mCherry::&lt;&gt; ΔrelA251::kan</i>	MG1655 RpoS-Mcherry x P1.N5777 to Km <sup>r</sup>
KM301	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δefp772::&lt;&gt; ΔrelA782::&lt;&gt;</i>	MH376 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C. Km <sup>s</sup> strain then transformed with pAM407 to Amp <sup>r</sup> and transduced with P1.KM189 to Tm <sup>r</sup>
KM307	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>rep<sup>+</sup>&lt;&gt; aspT[t8c]</i>	KM231 x pAM407 to Amp <sup>r</sup>
KM327	MG1655 <i>ΔlacIZYA::&lt;&gt; ΔgreA788::&lt;kan&gt;</i>	TB28 x P1.JW3148 to Km <sup>r</sup>
KM331	<i>ΔlacIZYA::&lt;&gt; rep<sup>+</sup>&lt;&gt; aspT[t8c]</i> <i>ΔgreA788::&lt;kan&gt;</i>	KM231 x P1.JW3148 to Km <sup>r</sup>
KM335	MG1655 <i>ΔlacIZYA::&lt;&gt; ΔgreA::&lt;&gt;</i> <i>ΔgreB740::&lt;kan&gt;</i>	KM338 x P1.JW3369 to Km <sup>r</sup>
KM336	<i>ΔlacIZYA::&lt;&gt; rep<sup>+</sup>&lt;&gt; aspT[t8c]</i> <i>ΔgreA788::&lt;&gt; ΔgreB740::&lt;kan&gt;</i>	KM339 x P1.JW3369 to Km <sup>r</sup>
KM337	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt; rep<sup>+</sup>&lt;&gt; aspT[t8c]</i>	KM231 x pAM403 to Amp <sup>r</sup>
KM338	<i>ΔlacIZYA::&lt;&gt; ΔgreA788::&lt;&gt;</i>	KM327 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM339	<i>ΔlacIZYA::&lt;&gt; rep<sup>+</sup>&lt;&gt; aspT[t8c]</i> <i>ΔgreA788::&lt;&gt;</i>	KM331 x pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
KM344	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat Δefp772::&lt;&gt;</i>	KM301 x P1.N6644 to Cm <sup>r</sup>

KM346	<i>ΔrelA782::&lt;&gt;</i> pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan aspT[t8c]</i> <i>rho[A243E]</i>	KM307 x P1.KM271
KM359	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan</i>	Plasmid-free segregant of KM273 formed on minimal medium subsequently transformed with pAM403 to Amp <sup>r</sup>
KM361	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan rho[A243E]</i>	Plasmid-free segregant of KM281 formed on minimal medium subsequently transformed with pAM403 to Amp <sup>r</sup>
KM367	pAM403 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan Δefp772::&lt;&gt;</i>	Plasmid-free segregant of KM277 formed on minimal medium subsequently transformed with pAM403 to Amp <sup>r</sup>
KM389	pAM407 ( <i>lac<sup>+</sup> uvrD<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan aspT[t8c]</i>	KM154 x P1.KM346 to Km <sup>r</sup>
KM391	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan aspT[t8c]</i>	Plasmid-free segregant of KM389 formed on minimal medium subsequently transformed with pAM403 to Amp <sup>r</sup>
KM393	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>Δrep729::kan Δefp772::&lt;&gt; rho[A243E]</i>	MH388 x pAM403 to Amp <sup>r</sup>
KM395	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan Δefp772::&lt;&gt;</i> <i>rho[A243E]</i>	KM393 x P1.KM271 to Tm <sup>r</sup>
KM398	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep729::kan aspT[t8c]</i> <i>rho[A243E]</i>	KM337 x P1.KM346
LC037	<i>ΔlacIZYA::&lt;&gt; rep<sup>+</sup>&lt;kan&gt; aspT[t8c]</i>	TB28 x P1.MKG121
MG1655	<i>rpoS-mCherry::&lt;&gt;</i>	(5)
RpoS-Mcherry		
MG1655	<i>rpoS-mCherry::&lt;kan&gt;</i>	Kenn Gerdes
RpoS-Mcherry		
Kan		
MH184	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat ΔyjeA782::kan</i>	JA033 × P1.JW4116 to Km <sup>r</sup>
MH280	<i>ΔlacIZYA::&lt;&gt; ΔyjeA782::kan</i>	TB28 × P1.JW4116 to Km <sup>r</sup>
MH298	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat ΔyjeK771::kan</i>	JA033 × P1.JW4106 to Km <sup>r</sup>
MH299	<i>ΔlacIZYA::&lt;&gt; Δefp772::kan</i>	TB28 × P1.JW4107 to Km <sup>r</sup>
MH300	<i>ΔlacIZYA::&lt;&gt; Δefp772::kan</i>	TB28 × P1.JW4107 to Km <sup>r</sup>
MH301	pAM403 ( <i>lac<sup>+</sup> rep<sup>+</sup></i> ) / <i>ΔlacIZYA::&lt;&gt;</i> <i>ΔuvrD::dhfr Δrep::cat Δefp772::kan</i>	JA033 × P1.JW4107 to Km <sup>r</sup>
MH303	<i>ΔlacIZYA::&lt;&gt; ΔyjeK771::kan</i>	TB28 × P1.JW4106 to Km <sup>r</sup>
MH363	<i>ΔlacIZYA::&lt;&gt; Δrep::cat ΔrelA782::kan</i>	N6577 × P1. JW2755 to

		Km <sup>r</sup>
MH364	<i>ΔlacIZYA::&lt;&gt; Δefp772::kan Δrep::cat</i>	MH300 × P1.PM412 to Cm <sup>r</sup>
MH372	<i>ΔlacIZYA::&lt;&gt; Δefp772::&lt;&gt;</i>	MH299 × pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
MH374	<i>ΔlacIZYA::&lt;&gt; Δefp772::&lt;&gt; Δrep::cat</i>	MH364 × pCP20 (3) to Amp <sup>r</sup> then plasmid-free Km <sup>s</sup> segregant identified after growth on LB at 42°C
MH376	<i>ΔlacIZYA::&lt;&gt; Δefp772::&lt;&gt; ΔrelA782::kan</i>	MH372 × P1. JW2755 to Km <sup>r</sup>
MH378	<i>ΔlacIZYA::&lt;&gt; Δefp772::&lt;&gt; Δrep::cat ΔrelA782::kan</i>	MH374 × P1. JW2755 to Km <sup>r</sup>
MH388	<i>ΔlacIZYA::&lt;&gt; Δrep729::kan Δefp772::&lt;&gt; rho[A243E]</i>	MH372 × P1.KM230 to Km <sup>r</sup> then <i>rho</i> allele screened by sequencing (6)
MKG08	<i>ΔlacIZYA::&lt;&gt; rep<sup>+</sup> &lt;kan&gt;</i>	<i>rep<sup>+</sup> &lt;kan&gt;</i> integration into N8210 using pKD46 (4)
MKG121	<i>ΔlacIZYA::&lt;&gt; rep<sup>+</sup> &lt;kan&gt; aspT[t8c]</i>	(7)
N4304	<i>ΔrelA251::kan ΔspoT207::cat</i>	TB28 × P1.N4304 to Km <sup>r</sup>
N5771	<i>ΔlacIZYA::&lt;&gt; ΔrelA251::kan</i>	N5771 × P1.N4304 to Cm <sup>r</sup>
N5777	<i>ΔlacIZYA::&lt;&gt; ΔrelA251::kan ΔspoT207::cat</i>	
N6268	<i>ΔlacIZYA::&lt;&gt; ΔruvABC::cat</i>	(8)
N6577	<i>ΔlacIZYA::&lt;&gt; Δrep::cat</i>	(9)
N6632	<i>ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr</i>	(9)
N6639	<i>pAM407 (lac<sup>+</sup> uvrD<sup>+</sup>) / ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr</i>	(9)
N6644	<i>pAM407 (lac<sup>+</sup> uvrD<sup>+</sup>) / ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr Δrep::cat</i>	(9)
N7120	<i>ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr Δrep::cat</i>	(9)
N7150	<i>pAM407 (lac<sup>+</sup> uvrD<sup>+</sup>) / ΔlacIZYA::&lt;&gt; rpoB*35 ΔuvrD::dhfr Δrep::cat</i>	(9)
N7153	<i>ΔlacIZYA::&lt;&gt; rpoB*35 ΔuvrD::dhfr Δrep::cat</i>	Plasmid-free segregant of N7150
N7154	<i>ΔlacIZYA::&lt;kan&gt; spoT1</i>	(9)
N7182	<i>ΔlacIZYA::&lt;&gt; ΔuvrD::dhfr Δrep::cat aspT[t8c]</i>	Isolated as a larger colony variant from a culture of N7120 grown in 56/2 glucose medium and spread on LB agar
N7187	<i>pAM407 (lac<sup>+</sup> uvrD<sup>+</sup>) / ΔlacIZYA::&lt;kan&gt; Δrep::cat spoT1</i>	(9)
N8210	<i>ΔlacIZYA::&lt;&gt; Δrep::cat aspT[t8c]</i>	P1.N7182 × TB28 to Cm <sup>r</sup>
PM567	<i>ΔlacIZYA::&lt;kan&gt; Δrep::cat spoT1</i>	Plasmid-free segregant of N7187
TB28	<i>ΔlacIZYA::&lt;&gt;</i>	(10)

## B) Other strains

BW25113	<i>rrnB3 ΔlacZ4787 hsdR514 Δ(araBAD)567 Δ(rhaBAD)568 rph-1</i>	(11)
JW0911	BW25113 <i>ΔaspC745::kan</i>	(11)
JW1839	BW25113 <i>Δeda775::kan</i>	(11)
JW2755	BW25113 <i>ΔrelA782::kan</i>	(11)
JW3148	BW25113 <i>ΔgreA788::kan</i>	(11)
JW3369	BW25113 <i>ΔgreB740::kan</i>	(11)
JW4014	BW25113 <i>ΔtyrB747747::kan</i>	(11)
JW4106	BW25113 <i>ΔyjeK771::kan</i>	(11)
JW4107	BW25113 <i>Δefp772::kan</i>	(11)
JW4116	BW25113 <i>ΔyjeA782::kan</i>	(11)
JW5604	BW25113 <i>Δrep729::kan</i>	(11)
AB1157	<i>araC14 thi-1 hisG4 Δ(gpt-proA)62 argE3 thr-1 leuB6 kdg51 rfbD1 lacY1 galK2 xyl-5 mtl-1 tsx-33 supE44 rac<sup>-</sup> mgl-51 rpsL31 qsr<sup>-</sup></i>	(1)
CS89	AB1157 <i>tls-1 eda-51::Tn10</i>	(12)

## References

1. Bachmann, B.J. (1996) In Neidhardt, F. C., Curtiss III, R., Ingraham, J. L., Lin, E. C. C., Low, K. B., Magasanik, B., Reznikoff, W. S., Riley, M., Schaechter, M. and Umberger, H. E. (eds.), *Escherichia coli and Salmonella cellular and molecular biology*. Second ed. ASM Press, Washington, DC, pp. 2460-2488.
2. Saxena, S. and Gowrishankar, J. (2011) Compromised factor-dependent transcription termination in a *nusA* mutant of *Escherichia coli*: spectrum of termination efficiencies generated by perturbations of Rho, NusG, NusA, and H-NS family proteins. *J. Bacteriol.*, **193**, 3842-3850.
3. Cherepanov, P.P. and Wackernagel, W. (1995) Gene disruption in *Escherichia coli*: Tc<sup>R</sup> and Km<sup>R</sup> cassettes with the option of Fip-catalyzed excision of the antibiotic-resistance determinant. *Gene*, **158**, 9-14.
4. Datsenko, K.A. and Wanner, B.L. (2000) One-step inactivation of chromosomal genes in *Escherichia coli* K-12 using PCR products. *Proc. Natl. Acad. Sci. U S A*, **97**, 6640-6645.
5. Maisonneuve, E., Castro-Camargo, M. and Gerdes, K. (2013) (p)ppGpp Controls Bacterial Persistence by Stochastic Induction of Toxin-Antitoxin Activity. *Cell*, **154**, 1140-1150.
6. Atkinson, J., Gupta, M.K., Rudolph, C.J., Bell, H., Lloyd, R.G. and McGlynn, P. (2011) Localization of an accessory helicase at the replisome is critical in sustaining efficient genome duplication. *Nucleic Acids Res.*, **39**, 949-957.
7. McGlynn, P. and Lloyd, R.G. (2000) Modulation of RNA polymerase by (p)ppGpp reveals a RecG-dependent mechanism for replication fork progression. *Cell*, **101**, 35-45.
8. Mahdi, A.A., Buckman, C., Harris, L. and Lloyd, R.G. (2006) Rep and PriA helicase activities prevent RecA from provoking unnecessary recombination during replication fork repair. *Genes Dev.*, **20**, 2135-2147.
9. Guy, C.P., Atkinson, J., Gupta, M.K., Mahdi, A.A., Gwynn, E.J., Rudolph, C.J., Moon, P.B., van Knippenberg, I.C., Cadman, C.J., Dillingham, M.S. *et al.* (2009) Rep Provides a Second Motor at the Replisome to Promote Duplication of Protein-Bound DNA. *Mol. Cell*, **36**, 654-666.
10. Bernhardt, T.G. and de Boer, P.A. (2004) Screening for synthetic lethal mutants in *Escherichia coli* and identification of EnvC (YibP) as a periplasmic septal ring factor with murein hydrolase activity. *Mol. Microbiol.*, **52**, 1255-1269.

11. Baba, T., Ara, T., Hasegawa, M., Takai, Y., Okumura, Y., Baba, M., Datsenko, K.A., Tomita, M., Wanner, B.L. and Mori, H. (2006) Construction of *Escherichia coli* K-12 in-frame, single-gene knockout mutants: the Keio collection. *Mol. Syst. Biol.*, **2**, 2006 0008.
12. Sharples, G.J. and Lloyd, R.G. (1991) Location of a mutation in the aspartyl-tRNA synthetase gene of *Escherichia coli* K12. *Mutat. Res.*, **264**, 93-96.