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The Highly Conserved Bacterial RNase YbeY Is Essential in *Vibrio cholerae*, Playing a Critical Role in Virulence, Stress Regulation, and RNA Processing

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Abstract

YbeY, a highly conserved protein, is an RNase in *E. coli* and plays key roles in both processing of the critical 3′ end of 16 S rRNA and in 70 S ribosome quality control under stress. These central roles account for YbeY’s inclusion in the postulated minimal bacterial genome. However, YbeY is not essential in *E. coli* although loss of *ybeY* severely sensitizes it to multiple physiological stresses. Here, we show that YbeY is an essential endoribonuclease in *Vibrio cholerae* and is crucial for virulence, stress regulation, RNA processing and ribosome quality control, and is part of a core set of RNases essential in most representative pathogens. To understand its function, we analyzed the RNA and ribosome profiles of a *V. cholerae* strain partially depleted for YbeY and other RNase mutants associated with 16 S rRNA processing; our results demonstrate that YbeY is also crucial for 16 S rRNA 3′ end maturation in *V. cholerae* and that its depletion impedes subunit assembly into 70 S ribosomes. YbeY’s importance to *V. cholerae* pathogenesis was demonstrated by the complete loss of mice colonization and biofilm formation, reduced cholera toxin production, and altered expression levels of virulence-associated small RNAs of a *V. cholerae* strain partially depleted for YbeY. Notably, the *ybeY* genes of several distantly related pathogens can fully complement an *E. coli* *ybeY* strain under various stress conditions, demonstrating the high conservation of YbeY’s activity in stress regulation. Taken together, this work provides the first comprehensive exploration of YbeY’s physiological role in a human pathogen, showing its conserved function across species in essential cellular processes.

Introduction

To thrive in diverse and changing environments, bacteria have to quickly sense and respond to a broad range of stimuli and signals. The ability to adapt to environmental changes is particularly important for pathogens during invasion of the host. Bacterial adaptation is often mediated through modulation of gene expression at the post-transcriptional level. A common mechanism to quickly sense and respond to a broad range of stimuli and signals is the post-transcriptional control of gene expression. Small RNAs (sRNAs) that control gene expression are perfectly paired to their target mRNAs coding for early virulence factors, whereas the exoribonuclease PNPass is involved in the cold stress response and global mRNA turnover [3,9]. In Gram-positive bacteria, RNase Y is the functional equivalent of RNase E in *E. coli* and affects virulence of *S. aureus* and *Streptococcus pyogenes* in silkworm and mouse models [3].

Small RNAs (sRNAs) that control gene expression are perfectly suited to initiate rapid regulatory circuits, as they do not require translation and can be turned on over quickly by various RNases [5,9]. For example, in *Vibrio cholerae*, several sRNAs have been identified with a role in pathogenesis, such as the quorum-sensing sRNAs Qyr1–4 and the ToxT activated sRNAs TarA and TarB [10,11]. In *S. aureus*, RNAIH acts as both an activator and repressor of early virulence factors, and 6S RNA of *Legionella pneumophila* is crucial for replication in host cells [12,13]. The function of regulatory sRNAs often relies on their interactions with accessory proteins, e.g. the RNA chaperone Hfq for stabilization of the sRNA/target mRNA interaction and various RNases for specific degradation of sRNAs and their target mRNAs [2,5].

One of the most recently identified RNases is YbeY, a highly conserved member of the UPF0054 protein family. It is found in...
Author Summary

Bacteria adapt and survive unfavorable environments by quickly changing their gene expression and physiology, for example as pathogens during infection of host cells. Gene expression is often determined by RNA turnover, a balance between transcription and RNA decay carried out by multiple RNases. The recently identified RNase YbeY was shown in E. coli to participate in rRNA maturation and 70 S ribosome quality control, however YbeY’s roles in other organisms and the extent of functional conservation is unknown. Here, we show that YbeY is an essential RNase in the pathogen Vibrio cholerae, critical for cell fitness and general stress tolerance. We demonstrate that YbeY is crucial for 16 S rRNA 3’ end maturation, assembly of functional 70 S ribosomes and ribosome quality control. Moreover, YbeY regulates virulence-associated small RNAs and its depletion leads to an overall reduction in pathogenesis, exemplified by significantly decreased biofilm formation, mouse colonization and cholera toxin production. We also show that YbeY belongs to a minimal core set of RNases essential in most representative pathogens. The multifaceted roles of YbeY in several essential cellular processes and its highly conserved function across bacterial species, suggest that YbeY could be an attractive new antimicrobial target.

almost all sequenced bacteria and is part of the postulated minimal bacterial gene set, encompassing 206 genes [14,15]. YbeY is not essential in E. coli and Sinorhizobium meliloti but its loss results in severe sensitivity to various stresses [14,16]. Studies of YbeY in E. coli have demonstrated that YbeY is a single-strand specific endoribonuclease with multiple physiological functions [16–19]. Deletion of ybeY in E. coli affects maturation of all three ribosomal RNAs (rRNAs), in particular 16 S rRNA. The deficiencies in rRNA processing caused by loss of YbeY function are augmented by additional mutations in rnc, rnr, and pnp, encoding Rvase III, RNase R, and PNPase, respectively. Correct maturation of the 3’ end of 16 S rRNA is essentially lost in ΔybeY Δrnc and ΔybeY Δpnp double mutants, making YbeY the first reported endoribonuclease shown to be involved in this critically important processing step [16]. 17 S rRNA and 16 S* rRNA, a truncated 16 S rRNA species, also strongly accumulate in a ΔybeY strain under heat stress, consistent with YbeY’s role in the heat-shock response in E. coli [18,20]. The efficiency and accuracy of translation is significantly lower in a ΔybeY strain, most likely due to maturation defects in the 30 S ribosomal subunits [16,19]. Protein mistranslation can be toxic to cells and therefore needs to be prevented. Interestingly, YbeY acting together with RNase R can remove defective 70 S ribosomes in a recently discovered mechanism of late-stage ribosome quality control in E. coli [18]. The latter process specifically targets fully assembled 70 S ribosomes containing immature or defective 30 S subunits [18]. An additional link to RNA metabolism is YbeY’s role in sRNA- mediated regulation of gene expression. Deletion of ybeY in S. meliloti produces a phenotype very similar to that of an hfg mutant, and several sRNAs were identified that potentially control expression of YbeY- and Hfq-dependent genes [21]. In view of YbeY’s multiple functions in bacterial RNA metabolism and the importance of RNases in pathogens, we decided to study YbeY’s physiological roles in a representative human pathogen.

Vibrio cholerae is the causative agent of cholera, a potentially lethal diarrheal disease that remains an important global health problem, having caused seven pandemics since 1817 [22–24]. This highly motile γ-Proteobacterium lives in both aquatic and mammalian intestinal environments. Its transmission occurs through contaminated water in regions with poor sanitation or by ingestion of contaminated shellfish, algae and aquatic plants, which are Vibrio’s ecological hosts [25]. Most pathogenesis genes of V. cholerae 7th pandemic O1 El Tor biotype strain N16961 are found on the larger of the two chromosomes including toxins, surface antigens and adhesins [26]. The two major virulence factors are the cholera toxin (CT), encoded by ctxAB on the CTXφ prophage [27], and the toxin co-regulated pilus (TCP), encoded by the tcp operon on the TCP pathogenicity island [28]. Following colonization of the small intestine, the A subunit of the AB5-toxin complex is taken into the intestinal epithelial cell via endocytosis leading to an increase of the host cell’s cAMP levels and causing an efflux of chloride ions and water.

Here, we show that YbeY is an essential gene in V. cholerae and that normal levels of its expression are crucial for virulence. A phylogenetic comparison of the essentiality of major RNases shows that YbeY is part of a small set of RNases essential in most representative pathogens. To understand its functional characteristics, we analyzed the rRNA and ribosome profiles of a V. cholerae strain after YbeY depletion, observing gradual accumulation of 16 S rRNA precursors and free ribosomal subunits. Compared to the 16 S rRNA processing RNase G [29] and the exonuclease RNase R, also shown to be involved in 16 S rRNA processing [16,30], only the loss of YbeY led to severe defects in 16 S rRNA 3’ end maturation and 70 S ribosome assembly. In the case of the multifunctional RNase E [31], the gene could not be deleted because it is essential, but a strain encoding RNase E:ΔCTD, in which the carboxy-terminal domain is disrupted, had no effect on 16 S processing. YbeY is also crucial for the virulence of V. cholerae, since a ΔybeY depletion strain that expresses reduced levels of YbeY fails to colonize infant mice intestines and its biofilm and CT production are significantly reduced compared to wild-type (Wt).

In addition, we experimentally identified several YbeY- and RNase E:ΔCTD-dependent sRNAs associated with V. cholerae virulence. Strikingly, ybeY genes from four distantly related pathogens can fully complement an E. coli ΔybeY strain, demonstrating the high conservation of YbeY activity across species.

Results

YbeY is part of a core set of RNases essential in most representative pathogens

To date, YbeY’s physiological roles have been studied in E. coli [16–19,32] and S. meliloti [14,21]. Its multifaceted functions in rRNA and sRNA metabolism make YbeY a key player among RNases. To gain further insight into the role of YbeY within the network of bacterial RNases, we carried out a comprehensive phylogenetic analysis of RNases in a selection of bacteria with a focus on human pathogens, assessing (i) the presence or absence of major RNases and (ii) their essentiality.

Figure 1 summarizes the results of our analysis for the main endo- and exoribonucleases in eleven intensively studied bacterial species, using available transposon collections and genome-wide gene-deletion studies [33–50]. As described in detail in Materials and Methods, this summary represents our best effort to analyze publically available databases, taking into account possible misclassification of the essential nature of individual RNases (e.g., transposon mutagenesis can miss mutants that grow very slowly or tolerate certain insertions; gene inactivation cannot detect essential functions covered by multiple genes). Bacterial species were sorted according to phylogeny based on the amino
acid sequence of each YbeY homolog; RNases were sorted according to their distribution, the most ubiquitous RNases being listed first.

This comparative analysis of RNases (Figure 1) reveals numerous patterns: a) YbeY is more often essential than not, indicating that the model organism E. coli is not always the most representative; b) the RNases of the postulated minimal bacterial genome [15] overlap well with the most ubiquitous RNases of both Gram-negative and Gram-positive bacteria, e.g. YbeY, RNase P, RNase III and PNPase; c) the majority of essential RNases are endonucleases, whereas bacterial exonucleases are functionally more redundant than endonucleases and are hence rarely

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**Figure 1. Essential RNases in human pathogens.** Compilation of major RNases in V. cholerae (Vc), E. coli (Ec), S. typhi (St), H. influenzae (Hi), P. aeruginosa (Pa), B. subtilis (Bs), S. aureus (Sa), S. pneumoniae (Sp), M. tuberculosis (Mt), H. pylori (Hp), and M. genitalium (Mg). The asterisk indicates RNases present in the minimal bacterial genome set [15]. RNases with dual endo- and exonuclease functions are listed twice, but are counted only once to assess the total number of genes. Blank squares indicate that no homolog for the respective RNase could be identified. The designation of RNases as putatively essential (E) and non-essential (N) is based on the availability of deletion or transposon mutants according to Materials and Methods. Current databases list these RNases as non-essential; follow-up experiments suggest these RNases could by essential (personal communication; BW Davies, LA Simmons, Y Furuta). Only mutants with transposon insertions in the last 10% of the gene are available. The key roles of RNases in mRNA (m), rRNA (r), tRNA (t) and sRNA (s) metabolism are indicated; other functions (o). The phylogenetic tree on top is based on alignment of various YbeY protein sequences using Geneious software.

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and ybeY in strain could be obtained. ybeZ in the arabinose transformed with a plasmid containing + under ybeY V. cholerae Genomic showed strain in the pY strain. Samples were taken from log phase cultures promoter. Thus, pY strain grown in the presence (VC0961)- ybeY mRNA were normalized S. typhi ybeY C6706 using standard in D pY strain was transferred to deletion is indicated (VC0960) locus in the chromosomal strain (VC0960) homolog, designated VC0960 [36]. To D V. cholerae pY mutant could be pY strain is identical to its parental pY cells 0.5), as shown above. The levels of ybeY mRNA were normalized to 5 S rRNA. The Wt strain grown in the absence of any carbon source and without the maintenance plasmid was set to 1. doi:10.1371/journal.ppat.1004175.g002

YbeY is essential for growth of V. cholerae

A large-scale, saturating transposon library of V. cholerae showed no hits for the ybeY homolog, designated VC0960 [36]. To experimentally verify the essentiality of ybeY in V. cholerae, we attempted to create a non-polar deletion of ybeY, which is part of the ybeZ operon (Figure 2A), in V. cholerae C6706 using standard allelic exchange [52]. However, chromosomal ybeY could be deleted only in a strain carrying a copy of ybeY on the arabinose inducible vector pBAD18 (henceforth referred to as ΔybeY) in the presence of 0.1% arabinose. In the absence of arabinose, no such non-polar deletion of ybeY could be obtained.

The growth rate of the ΔybeY pY strain is identical to its parental strain in LB medium in the presence of 0.1% arabinose (denoted as Ara+) (Figure 2B). When the ΔybeY pY strain was transferred to arabinose-free medium (denoted as Ara-) (Figure S1), cells showed a reduction in growth rate indicating YbeY depletion. If these cells were subcultured a second time into medium lacking arabinose (denoted as Ara-/Ara-) (Figure S1), cell growth was diminished to such an extent that we could not obtain enough cells for experimental measurements. An experimentally more convenient protocol for decreasing the expression of YbeY from pBAD18 is to shift the Ara+ cells to medium lacking arabinose but containing glucose, which decreases the 3',5'-cyclic AMP levels, lowering expression from the catabolite-repressed PBAD promoter. Thus, maximal depletion of YbeY was obtained by subculturing overnight cultures of the ΔybeY pY strain grown in the presence of 0.1% arabinose into medium that lacked arabinose but was supplemented with 0.2% glucose (denoted as Gluc+) (Figure 2B). After being switched to medium with glucose, ΔybeY pY cells initially grow similar to the wild-type (Wt) but grow slower after mid-exponential phase and stop growing at a significantly lower optical density (OD600) in stationary phase. No cell death or loss of viability was observed in late-stationary phase after YbeY depletion when cells were plated on arabinose-containing solid media to determine colony-forming units (data not shown). Since simply inoculating overnight cultures of cells grown with arabinose into medium containing glucose (Gluc+) gave robust YbeY depletion, we have chosen these conditions for most experiments described in this study, as they allowed us to maximally deplete...
YbeY levels in a controlled fashion (see also Figure 2C) without affecting cell viability.

The levels of ybeY mRNA in *V. cholerae* wild-type and the plasmid-containing mutant strain were determined by RT-qPCR (Figure 2C). Notably, the presence of the pBAD18 derivative containing the extrachromosomal copy of *ybeY* (pY) led to a moderate increase in ybeY mRNA levels due to leaky transcription in the absence of arabinose or glucose. Expression of *ybeY* is strongly induced by arabinose (Ara+). In contrast, *ybeY* expression was reduced to 20% of the endogenous wild-type *ybeY* levels when arabinose was removed from the media and glucose was added (Glu+).

Our ability to generate a *ybeY* deletion in *V. cholerae* C6706 only in vitro avoids the potential complications arising from the use of arabinose and glucose. Consequently, when Figure 3A). Mapping of both ends of 16 S rRNA in total RNA, 70 S ribosome levels are reduced to 20% of wild-type levels (Figure 2C, maximum YbeY depletion). The latter shows that although YbeY depletion; denoted as Ara+ and Ara+Gluc+ in Figure 3A). Mapping of the 5’ and 3’ termini of all rRNAs confirms the strong decrease in 16 S rRNA levels in the presence of glucose (Glu+), strongly induced by arabinose (Ara+). To determine the role of *V. cholerae* YbeY in rRNA maturation, we isolated total RNA from the wild-type and the Δ*ybeY* pY strain (Figure 3A). Δ*ybeY* pY cells grown in the presence of arabinose (Ara+Gluc+) showed strong accumulation of 17 S rRNA. We were able to detect an intermediate decrease of 16 S rRNA and a concomitant intermediate increase of 17 S precursor levels compared to the parental strain by switching the carbon source of the media from arabinose to glucose (Glu+). The level of aeration, source of LB medium etc. (data not shown).

**Depletion of YbeY in *V. cholerae* affects 16 S rRNA maturation and 70 S ribosome assembly**

Functional 70 S ribosomes are composed of 16 S, 23 S, and 5 S rRNAs that are processed from a larger RNA precursor. In *E. coli*, YbeY has been shown to be primarily involved in the maturation of both termini of 16 S rRNA and to also play a minor role in the 5′ maturation of 23 S and 5 S rRNAs [16]. Moreover, YbeY is essential for 16 S rRNA maturation in *V. cholerae* to date. To determine the role of *V. cholerae* YbeY in rRNA maturation, we isolated total RNA from the wild-type and the Δ*ybeY* pY strain (Figure 3A). Δ*ybeY* pY cells grown in the presence of arabinose (Ara+) showed strong accumulation of 17 S rRNA. We were able to detect an intermediate decrease of 16 S rRNA and a concomitant intermediate increase of 17 S precursor levels compared to the parental strain by switching the carbon source of the media from arabinose to glucose (Glu+). The level of aeration, source of LB medium etc. (data not shown).

YbeY of *E. coli* can degrade rRNA, mRNA and oligoribonucleotides in vitro [18]. Its active site has a highly conserved metal-coordinating histidine H3XH5XH motif that is characteristic to the UPF0054 protein family. The RNase activity of *V. cholerae* YbeY was confirmed by our demonstration that it was capable of degrading total *V. cholerae* rRNA, while its metal-dependency was confirmed by showing that the addition of EDTA inhibited this degradation (Figure S3A). Using an RNA hairpin and single-strand oligoribonucleotide substrates, we further demonstrated that *V. cholerae* YbeY is an endoribonuclease, whose substrate specificity is very similar to *E. coli* YbeY (Figure S3B, S3C).

To improve in vitro activity and to prevent aggregation of purified *V. cholerae* YbeY, we used a plasmid that encodes both GroES and GroEL to increase chaperone activity. The RNase activity of purified *V. cholerae* YbeY was slightly lower than that of purified *E. coli* YbeY, which could be due to the fact that YbeY was purified from *E. coli* BL21, a non-native host strain. In addition, we showed that YbeY together with RNase R of both *V. cholerae* and *E. coli* can degrade 70 S ribosomes isolated from the *V. cholerae* Δ*ybeY* pY strain grown under maximum YbeY depletion, but does not degrade *V. cholerae* wild-type ribosomes (Figure 4C, S3D). This is consistent with analogous experiments in *E. coli* [18], thereby demonstrating the conservation of the role of *V. cholerae* YbeY in ribosome quality control and the cross-species conservation of the YbeY-dependent ribosome quality control mechanism as *E. coli* enzymes recognize and degrade defective *V. cholerae* ribosomes.

**16 S rRNA maturation in *V. cholerae* mutant strains carrying transposon insertions in genes encoding RNase E, RNase G, or RNase R.**

To analyze the involvement of *V. cholerae* YbeY in maturation of 16 S rRNA in comparison to other RNases that are functionally associated with 16 S rRNA maturation in *E. coli*, we compared the 5′ and 3′ termini of 16 S rRNA from *V. cholerae* wild-type, the mgrC::Tn [36], rnc::Tn [36] and rnc::Tn mutant strains [36], and the Δ*ybeY* pY strain depleted of YbeY (Glu+) (Figure 5). In *E. coli*, RNase E (*rne*) and RNase G (*rng*) participate in the two-step, sequential maturation of the 5′ end of 16 S rRNA [29]. Although RNase E is essential for growth in *E. coli*, several *rne*::Tn mutants were found in *V. cholerae* transposon libraries [36,53]. However, all transposons were inserted downstream of the N-terminal domain (NTD) of RNase E that specifies the endonuclease activity,
Figure 3. Analysis of rRNA and ribosome profiles in *V. cholerae* ΔybeY. **A** Total RNA was isolated from C6706 Wt pY and the ΔybeY pY strain grown in the presence of arabinose or glucose as specified and analyzed by agarose gel electrophoresis. The positions of 23 S, 17 S, and 16 S rRNAs are indicated based on their mobility. **B** The 5' and 3' termini of 16 S rRNA from C6706 Wt pY and the ΔybeY pY strain were mapped as described in detail in Materials and Methods. "P" and "M" specify the positions of bands derived from the precursor and mature forms of 16 S rRNA. **C** Ribosome profiles for C6706 Wt pY and the ΔybeY pY strain (top); quantitation of polysomes, 70 S, 50 S and 30 S ribosomes (bottom pie charts). "pY" indicates that ybeY is expressed from a plasmid. Ara+, cells were grown in LB in the presence of arabinose. Gluc+, cells were grown in LB in the presence of glucose. Ara+/Gluc+, intermediate YbeY depletion by switching the carbon source of the ΔybeY pY strain in early exponential phase from arabinose to glucose (for details see Materials and Methods).

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YbeY’s Functional Role in V. cholerae

confirming the essentiality of its nuclease activity in V. cholerae. The C-terminal domain (CTD) functions as a scaffold for various interacting proteins that make up the degradosome and was recently shown to be required for binding to 30 S subunits of E. coli [31,54]. Since multiple mutants with transposon insertions within the CTD of RNase E are available in V. cholerae [36,53], a fully functional degradosome may not be essential for the viability of V. cholerae.

The transposon of the representative rnc::Tn mutant we chose to investigate further is located between segment A and the first RNA binding domain of RNase E [31]. Therefore, this mutant, designated as rnc-CTD::Tn, lacks the full C-terminal scaffolding domain as confirmed by RT-qPCR (data not shown).

Figure 4. Comparison of ribosome profiles and 16 S rRNA maturation in V. cholerae ΔybeY and E. coli ΔybeY. A) Ribosome profiles for V. cholerae C6706 Wt pY and the ΔybeY pY strain, and E. coli MC4100 Wt and the ΔybeY strain (top); quantitation of polysomes, 70 S, 50 S and 30 S ribosomes (bottom pie charts). “pY” indicates that ybeY is expressed from a plasmid. V. cholerae Wt pY was grown in LB in the presence of arabinose (Ara+) and V. cholerae ΔybeY pY was grown in LB in the presence of glucose for maximum depletion (Gluc+). E. coli cells were grown in LB medium without additional carbon source. B) Mapping of 5’ and 3’ termini of 16 S rRNA in total RNA, 30 S ribosomal subunits and 70 S ribosomes from C6706 Wt pY (W) and the ΔybeY pY strain (Δ), and E. coli MC4100 Wt (W) and the ΔybeY strain (Δ). rRNA was isolated from samples shown in A). “P” and “M” specify the positions of bands derived from the precursor and mature forms of 16 S rRNA. C) In vitro ribosome quality control by V. cholerae (Vc) and E. coli (Ec) YbeY together with RNase R. 70 S ribosomes of a V. cholerae ΔybeY pY strain upon maximum YbeY depletion were incubated with YbeY, RNase R, or a mixture of YbeY and RNase R from E. coli or V. cholerae as indicated. The positions of 23 S and 16 S rRNAs are indicated based on their mobility.

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end processing is reduced considerably upon depletion of YbeY as well as in the absence of RNase G, but is unaffected in both rnr-CTD::Tn and mc::Tn mutants (Figure 5, top panel). Notably, no mature 3' end was detected in total RNA samples from the V. cholerae rnr::Tn mutant, in contrast to E. coli, which still contains a substantial amount of the mature form in the absence of RNase G [29]. These results were confirmed by agarose gel electrophoresis, showing a 17 S-like precursor in total RNA of the rnr::Tn mutant (Figure 5, bottom panel). Maturation of the 3' end of 16 S rRNA is defective upon maximum depletion of YbeY in V. cholerae but not in the mc-CTD::Tn, mc::Tn and mc::Tn mutants, demonstrating that YbeY is a key RNase required for processing of the critical 16 S rRNA 3' end (Figure 5, middle panel).

In both the 30 S subunits and 70 S ribosomes of the V. cholerae rnr::Tn mutant, additional, although still incomplete, processing of the 3' end was observed, showing that low-level maturation occurs in the ribosomal context. The 70 S ribosome of the V. cholerae rnr::Tn mutant contains immature 3' ends, which is different from the V. cholerae YbeY-depleted ΔybeY Y1 strain. This is consistent with the fact that the V. cholerae rnr::Tn has no apparent growth phenotype (data not shown) and ribosomes with immature 16 S rRNA 3' termini can function in contrast to ribosomes with immature 3' termini [55–57].

Sucrose gradient analysis of V. cholerae ribosomes shows no defects in the absence of RNase G, RNase E:ΔCTD, and RNase R compared to the wild-type (Figure S4), possibly due to correct 16 S rRNA 3' maturation. Therefore, among the RNases whose function we assessed, YbeY is the only RNase crucial for 3' processing of 16 S rRNA and its assembly into 70 S ribosomes in V. cholerae.

YbeY affects regulation of virulence associated small RNAs

Expression of critical virulence genes in various pathogens is often regulated by small RNAs (sRNAs). In many cases, regulation by sRNA depends on the RNA chaperone Hfq with a subsequent involvement of RNase E [58]. In S. meliloti, YbeY function clearly affects the regulation of certain sRNAs and their target mRNAs [21]. To investigate a possible role of V. cholerae YbeY in sRNA regulation, we selected five sRNAs thought to be important for pathogenicity: MicX and VrrA, which regulate the expression of outer membrane proteins [59,60]; TarB, which targets the colonization factor TcpE [61] and the Vibrio seventh pandemic regulator VspR [62]; Qrr1–4 sRNAs, which control quorum sensing and those virulence genes that are regulated by quorum sensing [63]; and the regulator 6 S RNA, which binds to and thereby affects transcription of RNA polymerase σ70-driven genes [12].

Expression patterns of MicX, VrrA, TarB, Qrr1–4 and 6 S RNA were monitored by Northern blot analysis of total RNA isolated from ΔybeY cells upon maximum YbeY depletion and from mc-CTD::Tn cells (Figure 6). Steady state levels of MicX and TarB sRNAs were significantly reduced upon YbeY depletion compared to the parental strain, while levels of Qrr1–4 sRNAs were elevated (Figure 6A). In contrast, the mc-CTD::Tn mutant, which harbors an RNase E mutant lacking the docking domain for Hfq and other components of the degradosome [31], showed no changes in MicX and TarB sRNA levels but strongly increased VrrA and Qrr1–4 sRNA levels (Figure 6B). 6 S RNA levels did not change in either of the mutant strains (Figure 6A and B). Quantitation of sRNA levels was performed using 3 S rRNA as a loading control (Figure 6C and D). Taken together, these results

Figure 5. 16 S rRNA maturation in V. cholerae mutant strains with transposon insertions in genes encoding RNase E (rne-CTD::Tn), RNase G (rng::Tn), or RNase R (rnr::Tn). Mapping of 5' and 3' termini of 16 S rRNA in total RNA, 30 S ribosomal subunits and 70 S ribosomes from C6706 Wt pY (W), ΔybeY pY (Δ), rne-CTD::Tn (E), rng::Tn (G) and rnr::Tn (R); “P” and “M” specify the positions of bands derived from the precursor and mature forms of 16 S rRNA (top and middle panel). Analysis of total RNA by agarose gel electrophoresis; the positions of 23 S, 17 S and 16 S rRNAs are indicated based on their mobility (bottom panel). “Pf” indicates that ybeY is expressed from a plasmid. V. cholerae Wt pY was grown in LB in the presence of arabinose (Ara-+) and V. cholerae ΔybeY pY was grown in LB in the presence of glucose for maximum depletion (Glu+); all other strains were grown in LB medium without additional carbon source. doi:10.1371/journal.ppat.1004175.g005
show a clear role of *V. cholerae* YbeY in sRNA regulation, different from that of the traditional Hfq/RNase E-mediated system.

**YbeY plays an important role in *V. cholerae* pathogenesis**

Certain RNases are important for pathogens to survive the fluctuating conditions during host infection and to control the expression of many virulence factors [64]. We have shown YbeY to be an RNase in *V. cholerae* that plays a role in regulating the levels of several virulence-associated sRNAs. To study YbeY’s role in *V. cholerae* pathogenesis, we investigated the effect of YbeY’s depletion on a number of specific virulence factors of *V. cholerae*.

Initially, we observed an apparent loss of pigmentation in the Δ*ybeY* strain upon maximum YbeY depletion to 20% of wild-type YbeY levels (Figure 7A). Also, overnight biofilm formation in static LB cultures was dramatically reduced upon maximum YbeY depletion, compared to wild-type and to Δ*ybeY* pY cultures grown in the presence of arabinose (Figure 7B). Additionally, depletion of YbeY significantly reduced CT production of Δ*ybeY* pY cells (Figure 7C). Exposure to bile salts resulted in a two to four order of magnitude drop in survival of the Δ*ybeY* pY strain upon YbeY depletion, 1 to 3 hours after cells were shifted to media lacking arabinose (Figure 7D). Finally, as depletion of YbeY clearly affects multiple virulence factors, we assessed YbeY’s overall ability to colonize and persist in an infant-mouse colonization model (Figure 7E). Using a competition assay, we grew the wild-type and Δ*ybeY* pY strain in the absence of arabinose prior to inoculation of infant-mice. As shown in Figure S1, depletion of YbeY without glucose results in an intermediate growth phenotype allowing us to obtain an equal number of cells of the wild-type and Δ*ybeY* mutant strain in early exponential phase. We found a striking reduction in colonization by the Δ*ybeY* pY strain relative to the parental strain, when both strains were grown in the absence of arabinose prior to inoculation (Figure 7E). Only a minor colonization defect was observed with strains grown in the

**Figure 6. sRNA analysis in *V. cholerae ΔybeY* and *rne-CTD::Tn*.** Northern blot analysis of MicX, VrrA, TarB, Qrr1–4 and 6 S RNA in (A) *V. cholerae ΔybeY* pY and (B) *V. cholerae rne-CTD::Tn*. Total RNA was isolated from C6706 Wt, Wt pY, Δ*ybeY* pY and *rne-CTD::Tn* grown in LB medium and analyzed by denaturing 6% polyacrylamide gel electrophoresis followed by Northern blot hybridization. The sizes of sRNAs were in accordance with published data. A 5 S rRNA-specific probe was used as a loading control. Hybridization signals were evaluated by phosphorimager analysis in (C) and (D); the levels of various sRNAs were normalized to 5 S rRNA. The Wt strain was set to 1. “pY” indicates that ybeY is expressed from a plasmid. Gluc+, cells were grown in the presence of glucose.

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presence of arabinose prior to inoculation. This lack of complete complementation is probably due to the absence of arabinose in the intestinal tract of mice, allowing for some/slight YbeY depletion. Taken together, these results suggest that YbeY plays a critical role during multiple stages of the \textit{V. cholerae}'s infection cycle.

YbeY plays a central role in stress regulation of \textit{V. cholerae}.

The phenotype of \textit{DybeY} deletion mutants in \textit{S. meliloti} and \textit{E. coli} is extremely pleiotropic, as they exhibit a strong sensitivity to a wide range of physiological stresses [14,16]. To analyze the importance of YbeY function in protecting \textit{V. cholerae} against stress, we tested the sensitivity of the \textit{V. cholerae \textit{DybeY} pY} strain to a broad variety of stresses targeting key cellular processes after YbeY had been depleted by growth in glucose. These stresses include antibiotics targeting protein synthesis, transcription, and cell wall synthesis, the oxidative stress $H_2O_2$, the DNA-damaging agent ultraviolet radiation and heat (Figure 8).

Cell growth was tested on plates by serial dilution of overnight cultures of \textit{V. cholerae} wild-type and \textit{DybeY pY} cells grown in the presence of arabinose; to deplete YbeY, glucose was present in the plating medium as indicated. Under non-stress conditions (37°C), \textit{DybeY pY} showed similar growth upon YbeY depletion compared to wild-type, although mutant colonies at the highest dilutions were smaller than wild-type colonies due to their reduced growth rate (Figure 8A). Although \textit{ybeY} is essential, no cell death was observed under these conditions, most likely because \textit{ybeY}'s leaky expression still reaches approximately 20% of the endogenous wild-type \textit{ybeY} levels (Figure 2B).

In general, cell growth of the \textit{V. cholerae \textit{DybeY} pY} strain on plates supplemented with glucose and one of several stress agents was drastically reduced compared to the parental strain (Figure 8A). Since YbeY has a major role in 16 S rRNA maturation, we tested three different antibiotics that target the 30 S ribosomal subunit in a different way, tetracycline, gentamycin and kasugamycin. The \textit{DybeY pY} strain showed a severe increase in sensitivity compared to wild-type, although mutant colonies at the highest dilutions were smaller than wild-type colonies due to their reduced growth rate (Figure 8A). Although \textit{ybeY} is essential, no cell death was observed under these conditions, most likely because \textit{ybeY}'s leaky expression still reaches approximately 20% of the endogenous wild-type \textit{ybeY} levels (Figure 2B).

In general, cell growth of the \textit{V. cholerae \textit{DybeY} pY} strain on plates supplemented with glucose and one of several stress agents was drastically reduced compared to the parental strain (Figure 8A). Since YbeY has a major role in 16 S rRNA maturation, we tested three different antibiotics that target the 30 S ribosomal subunit in each in a different way, tetracycline, gentamycin and kasugamycin. The \textit{DybeY pY} strain showed a severe increase in sensitivity upon YbeY depletion to all of these antibiotics. A similar effect was observed with antibiotics targeting the 50 S ribosomal subunit, chloramphenicol and erythromycin. Additionally, we found that the \textit{DybeY pY} strain also exhibited increased sensitivity to inhibition of RNA synthesis by rifampicin and cell wall synthesis.
by both ampicillin and cefotaxime. As *V. cholerae* is exposed to oxidative stress during host infection and UV radiation outside of the host, both stresses were tested as well, showing a consistent decrease in protection against oxidative and UV stress upon YbeY depletion (Figure 8A).

In *E. coli*, YbeY is an important factor for rRNA maturation even at 37°C but becomes essential upon temperature shift to 45°C as shown by a complete loss of mature 16 S rRNA and cell viability [16,18,19]. YbeY depletion in a *V. cholerae* ΔybeY pY strain grown in glucose also causes a growth defect at 45°C after 3 hours compared to wild-type (Figure 8B), however only a two to three orders of magnitude drop in survival was consistently observed, in contrast to *E. coli*’s overall loss of viability at elevated temperatures [see Figure 9A]. This difference might in part be *V. cholerae* specific but may also be due to the low background levels of YbeY still present in the *V. cholerae* depletion strain. Overexpression of *ybeY* does not provide additional heat protection to *V. cholerae* because the wild-type strain with and without the *ybeY* overexpression plasmid showed a similar level of heat tolerance (data not shown). Interestingly, a cold-sensitive phenotype was found upon depletion of YbeY in a *V. cholerae* ΔybeY pY strain at 18°C (Figure 8C). A similar cold-sensitivity was not observed in *E. coli*, further illustrating the disparity in response to changes in temperature between *V. cholerae* and *E. coli* depleted of YbeY.

YbeY’s activity in stress regulation and rRNA maturation is highly conserved among evolutionary distant pathogens

YbeY is a highly conserved protein found in almost all sequenced bacteria. To determine the level of functional conservation, we complemented the *E. coli* ΔybeY strain – grown under a variety of stress conditions – using constitutively expressed *ybeY* of four distantly related human pathogens, *V. cholerae*, *P. PLOS Pathogens | www.plospathogens.org 11 June 2014 | Volume 10 | Issue 6 | e1004175

Figure 8. Sensitivity of *V. cholerae* ΔybeY to various stresses. A) C6706 Wt pY and ΔybeY pY cells were grown overnight in LB medium supplemented with arabinose, subsequently diluted to an OD600 0.1 and then spotted as a dilution series (1:10) onto LB plates supplemented with various antibiotics or H₂O₂ or irradiated with UV as indicated. Cells were grown in the presence of glucose (Gluc+) or arabinose (Ara+) as indicated. B) To determine heat-sensitivity of C6706 Wt pY and ΔybeY pY cells, early exponential cultures supplemented with glucose were incubated for 3 h at 37°C and 45°C before spotting as a dilution series (1:10) onto LB plates supplemented with glucose (Gluc+). Cells were then grown for 18 h at 37°C. C) To determine cold-sensitivity of C6706 Wt pY and ΔybeY pY cells, cultures were spotted as a dilution series (1:10) onto LB plates supplemented with glucose (Gluc+). Cells were then grown for 2 days at 37°C and 18°C as indicated.
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YbeY’s Functional Role in V. cholerae

YbeY’s Functional Role in V. cholerae playing a central role in RNA metabolism

YbeY is the first endoribonuclease of E. coli shown to play a direct or indirect role in processing of the 16 S rRNA 3’ terminus [16,18]. However, most of what we know about rRNA processing comes primarily from studies in E. coli [31,63], while relatively little information is available in other organisms. Here, we have shown that V. cholerae YbeY is also a metal-dependent endoribonuclease, although in contrast to E. coli, ybeY is essential in V. cholerae (Figure 2). Gradual depletion of YbeY in V. cholerae results in gradual accumulation of 16 S RNA precursors that are defective in maturation of both ends, along with a gradual decrease in the efficiency of ribosome assembly (Figure 3). Similar to E. coli, where YbeY plays a minor role in 5’ maturation of 23 S and 5 S rRNAs [16], YbeY does not appear to be required for the maturation of 23 S and 5 S rRNAs in V. cholerae. We also examined 16 S rRNA processing in V. cholerae mutants of RNases associated with 16 S rRNA maturation in E. coli, the 5’ end processing RNases E and G and RNase R. The latter exoribonuclease plays an important role in 70 S ribosome quality control together with YbeY [18] and has been shown to largely bind to the ribosome close to the 5’ end of 16 S rRNA [66]. Using an mecTn mutant (me-cTDD::Tn) that contains the essential N-terminal nuclease domain but lacks the C-terminal degradosome scaffold [31], we have shown that an intact RNase E nuclease domain is sufficient for 5’ processing of 16 S rRNA (Figure 5). As expected, a 5’ processing defect was observed in the rng::Tn mutant. 3’ maturation was not affected in the me-cTDD::Tn and rng::Tn mutants, and lack of RNase R had no effect on 5’ or 3’ processing.

Similar to E. coli [16], depletion of YbeY leads to processing defects at both the 5’ and 3’ ends of 16 S rRNA (Figure 4). The role of YbeY in 5’ maturation of 16 S rRNA is likely indirect. It is possible that 5’ processing of 16 S rRNA is dependent on 3’ processing, which is in accord with a recent report showing that in E. coli 5’ processing proceeded much less efficiently in the absence of four exoribonucleases thought to be involved in 3’ maturation of 16 S rRNA [30]. Moreover, the 30 S particles in the YbeY-depleted samples contained mostly 16 S rRNA precursors, indicating that correct 16 S rRNA maturation may be required for efficient 70 S ribosome assembly and that the final maturation of 16 S rRNA occurs on the ribosome.

We also demonstrated that 70 S ribosome quality control mediated by YbeY and RNase R is not limited to E. coli [18]. Defective V. cholerae 70 S ribosomes were degraded by the combined action of V. cholerae YbeY and RNase R (Figure 4 and S3). Similar to YbeY, RNase R is also present in many bacteria. One could easily envision that YbeY functions alongside Hfq and replaces the RNase E-mediated recruitment of interacting partners that function of the commonly used RNase E for a certain subset of sRNAs and TarB is mediated by Hfq [62,71]. One could easily envision that YbeY functions alongside Hfq and replaces the function of the commonly used RNase E for a certain subset of sRNAs. Conversely, YbeY may also target certain sRNAs in an Hfq-independent manner as it has been shown for PNPase in E. coli [72]. Moreover, consistent with current knowledge of sRNA regulation we observed differential sRNA levels of VrrA and Qrr1–4 in V. cholerae (Figure 6A). It is currently not known, whether YbeY requires Hfq to do so. In V. cholerae, regulation of quorum sensing sRNAs and TarB is mediated by Hfq [62,71]. One could easily envision that YbeY functions alongside Hfq and replaces the function of the commonly used RNase E for a certain subset of sRNAs. Conversely, YbeY may also target certain sRNAs in an Hfq-independent manner as it has been shown for PNPase in E. coli [72]. Moreover, consistent with current knowledge of sRNA regulation we observed differential sRNA levels of VrrA and Qrr1–4 in V. cholerae RNase E mutant which lacks the degradosome scaffold domain (me-cTDD::Tn) (Figure 6B), but saw no changes for sRNAs MicX and TarB that are targeted by YbeY. Although the essential nuclease activity of RNase E is maintained in me-cTDD::Tn, the docking site for various degradosome components such as Hfq and PNPase is absent, impeding the RNase E-mediated recruitment of interacting partners that are required for certain sRNAs. These data hence establish YbeY as an important player in sRNA regulation alongside Hfq, RNase E and PNPase, and add to its key role in bacterial RNA metabolism.
YbeY affects multiple virulence factors and the overall stress response of V. cholerae

Virulence factors are gene products that improve bacterial survival during host infection. We demonstrate that depletion of YbeY impedes V. cholerae’s virulence by affecting virulence factors at multiple stages along the pathogenesis cycle (Figure 7). First, YbeY depletion reduces the level of pigmentation. Pigments like melanin protect cells against UV radiation, which is a major source of stress for pathogens outside the host and was previously shown to regulate expression of virulence factors [73]. Second, biofilm formation is drastically reduced upon YbeY depletion. Biofilms are highly organized microbial communities that are characterized by the ability to resist diverse stresses like antibiotics and host immune systems [74]. Biofilms are central to pathogenesis of many bacterial infections [73]. Third, YbeY depletion significantly reduces cholera toxin (CT) production. Colonization of the small bowel by V. cholerae must occur before CT is secreted into the intestinal epithelial cells and causes severe diarrhea. Therefore, YbeY-depleted cells that colonize the intestine are substantially less toxic than the parental strain. Fourth, lack of YbeY highly sensitizes the V. cholerae ybeY mutant to bile salts, which are antimicrobial substances present in the small intestines of mammals and one of the first stress factors encountered by the bacteria after passage through the acidic stomach. Lastly, intestinal colonization by the V. cholerae ybeY mutant is almost completely lost upon YbeY depletion in competition with the wild-type strain in infant mice, illustrating the overall reduced in vivo fitness or reduced ability to establish an infection. This is consistent with YbeY being one of the 507 genes that are highly expressed in both stool samples from cholera patients and during mid-exponential growth in rabbit ileal loops compared to growth in LB [76,77]. Virulence defects observed upon YbeY depletion in V. cholerae could be partly indirect, since YbeY affects ribosome biogenesis and thereby globally affects protein synthesis.

Figure 9. Complementation of E. coli ΔybeY by ybeY of various pathogens. A) E. coli MC4100 Wt pY and the ΔybeY pY strain grown in LB medium were serially (1:10) diluted and spotted onto LB plates containing various antibiotics or H2O2 treated with heat (45°C) or UV (60 J/m²) as indicated. “pY_Ec” refers to a plasmid expressing ybeY of E. coli, similarly V. cholerae N16961 (pY_Vc), P. aeruginosa PAO1 (pY_Pa), M. tuberculosis H37Rv (pY_Mt), and S. pneumoniae R6 (pY_Sp). B) Total RNA was isolated from E. coli MC4100 transformed with the empty vector, and the E. coli ΔybeY strain transformed with plasmids containing ybeY from various bacteria as indicated. RNA was analyzed by agarose gel electrophoresis. The positions of 23S, 17S, 16S and 16S* rRNAs are indicated based on their mobility.

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The reduced virulence of the \textit{ybeY} mutant is, however, opposite to that expected from the relative fall in TarB levels and rise in Qrr1–4 levels upon \textit{YbeY} depletion; low TarB and elevated Qrr1–4 levels generally correlate with increased expression of specific virulence genes [61,62,71,78]. Virulence, as defined by successful penetration of the host’s defense mechanisms, colonization and toxigenesis, is nonetheless an intricate phenomenon and represents the net result of the coordinated expression of hundreds of genes including sRNAs, that are subject to multiple regulatory circuits [10,79,80]. While \textit{YbeY}’s exact role in the regulation of virulence-associated sRNAs and their effect on various virulence factors is unclear, \textit{YbeY} evidently plays a crucial role in \textit{V. cholerae} pathogenesis.

Stress adaptation is key to establishing a successful infection. \textit{YbeY} was originally discovered in \textit{S. meliloti} as a stress regulator crucial to establish a chronic intracellular infection required for the nitrogen-fixing symbiosis within its host plant \textit{Medicago sativa} [14]. In \textit{E. coli}, deletion of \textit{ybeY} causes a pleiotropic stress phenotype, especially to heat [16]. Hence, \textit{YbeY} was initially identified as a heat shock protein [20]. In \textit{V. cholerae}, we showed that \textit{YbeY} depletion drastically impairs the stress response to a wide variety of stress agents. Its remarkably pleiotropic phenotype (Figure 8A) distinguishes it from most RNase mutants studied so far, which typically show fewer phenotypic traits. However, \textit{YbeY} of \textit{V. cholerae} does not act like a heat shock protein. Depletion of \textit{YbeY} results only in a modest decrease of cell survival after heat treatment compared to the wild-type (Figure 8B). On the other hand, unlike in \textit{E. coli}, a modest cold-sensitive phenotype was found upon \textit{YbeY} depletion in \textit{V. cholerae ybeY} at 18°C (Figure 8C). Cold-sensitivity is a characteristic of ribosome assembly defects, since lower temperatures can stabilize incorrect ribosome intermediates [81], and is a well-established phenotype of RNase mutants lacking PNPase, RNase PH or RNase R [82,83]. Hence, cold-sensitivity is in agreement with \textit{YbeY}’s key role in RNA metabolism.

\textit{YbeY} is part of a core set of bacterial RNases representing an attractive antimicrobial drug target

Based on high sequence conservation, \textit{YbeY} is found in virtually all sequenced bacteria. Orthologs of \textit{ybeY} are much less conserved in eukaryotes. So far, no orthologs could be identified in sequenced Fungi and Archaea although they are present in some higher eukaryotes, including humans. We have demonstrated here that \textit{YbeY}’s function in stress regulation and rRNA maturation is
highly conserved in bacteria as ybeY orthologs of four distantly related pathogens, S. pneumoniae, M. tuberculosis, P. aeruginosa, and V. cholerae, could fully complement an E. coli ΔybeY mutant subjected to a variety of stress agents and could correctly mature 16 S rRNA of E. coli during heat treatment (Figure 9). This is notable as conserved proteins do not always retain their specific characteristics, e.g. MazG of M. tuberculosis. This conserved NTP-pyrophosphohydrolase was shown to have a distinct function in M. tuberculosis compared to E. coli in response to starvation and oxidative stress [84].

Using a comprehensive phylogenetic analysis of major RNases in a selection of important bacterial pathogens (Figure 1), we showed that YbeY is more often essential than not and is part of a minimal core set of RNases, consistent with its remarkable level of functional conservation. While the overarching mechanisms by which organisms process RNA are conserved, our analysis also shows the disparity of RNases and their essentiality among different organisms. Thus, RNA maturation and degradation machineries necessitate the implementation of a set of RNases, which may vary from organism to organism, to fulfill all required functions. Altogether, the relatively low number of essential RNases underlines functional redundancy within groups of RNases and highlights the fundamental role of YbeY as a bacterial RNase.

Novel drug targets are crucial to combat the rapid rise of antibiotic resistance. The majority of today’s antibiotics have been developed against essential components of central cellular pathways. New potential targets worth evaluating include bacte- ria-specific proteases, aminoacyl-tRNA synthetases, RNA-modification enzymes, and RNases. For example, the essential process of RNA turnover via RNases is considered rich in candidate antimicrobial targets [63]. The RNase YbeY represents an important new promising drug target. We have demonstrated that YbeY in V. cholerae plays an essential role in various aspects of RNA metabolism and overall pathogenesis (Figure 10). Depletion of YbeY in V. cholerae limits growth and increases the organism’s sensitivity towards stress, making YbeY well suited for the development of target-specific antibiotics in whole-cell screening assays based on differential sensitivity of target-depleted and complemented strains. Such an approach was used successfully to discover platensimycin, a new class of broad-spectrum antibiotics for Gram-positive bacteria [85]. The availability of a suitable model host is also crucial for early antibiotic development [86]. Since depletion of YbeY in V. cholerae significantly reduces colonization of the pathogen in infant mice as well as expression of numerous virulence factors, a mouse model can be adapted for such a purpose. Although functionally associated with a well-established antibiotic target, the ribosome (Figure 10), YbeY is so far unexploited as a drug target and its use as a drug target might lead to the discovery of completely novel antibiotic scaffolds. A YbeY-specific inhibitor could also be used in combination with other antibiotics for enhanced antimicrobial activity, similar to combining silver and vancomycin [87] or rifampicin and acyldepsipeptide that activates the CbpP protease [88]. Considering YbeY’s high level of conservation, its essential nature in many pathogens and its ability to sensitize pathogens by disrupting stress tolerance and virulence, a YbeY-specific antibiotic could have broad-spectrum antimicrobial activity.

Materials and Methods

Ethics statement

The animal experiments were performed with protocols approved by Harvard Medical School Office for Research Protection Standing Committee on Animals. The Harvard Medical School animal management program is accredited by the Association for the Assessment and Accreditation of Laboratory Animal Care, International (AAALAC), and meets National Institutes of Health standards as set forth in the Guide for the Care and Use of Laboratory Animals (DHHS Publication No. (NIH) 85–23 Revised 1996). The institution also accepts as mandatory the PHS Policy on Humane Care and Use of Laboratory Animals by Awarded Institutions and NIH Principles for the Utilization and Care of Vertebrate Animals Used in Testing, Research, and Training. There is on file with the Office of Laboratory Animal Welfare (OLAW) an approved Assurance of Compliance (A3431-01).

General

DNA and RNA-DNA chimeric oligonucleotides were obtained from IDT or Eurofins MWG Operon. Sequences of oligonucle- oides used in this study are summarized in Table S1.

Genome analysis of essential RNases in human pathogens

RNase genes were identified as putatively essential based on comparison of various deletion or transposon libraries in V. cholerae C6706 ([36,53]; this work), E. coli MG1655 [39,40], S. typhi Ty2 [37,45], H. influenzae Rd KW20 [33,34], P. aeruginosa PA14 ([46]; http://ausubellab.mgh.harvard.edu/cgi-bin/pa14/home.cgi), B. subtilis 168 [44], S. aureus NCTC 8325 [38], S. pneumoniae TIGR4 [48], M. tuberculosis H37v [42,49,50], H. pylori G27 [47], and M. genitalium G37 [41]. RNases were designated as essential if no deletion or transposon mutant was available for the respective open reading frame. For RNase E, several libraries contained mutants with transposon insertions in the second half of the gene corresponding to the C-terminal docking domain of RNAse E, but no transposon insertions in the first half of the gene which corresponds to the essential RNase domain of RNAse E [51]; in these cases, RNAse E was termed essential. RNases were designated as non-essential when multiple deletion or transposon mutants were available, with transposon insertions randomly distributed within the respective open reading frame. The identity of individual RNases was confirmed by BLAST searches (NCBI).

Strain construction and DNA manipulations

To generate a non-polar deletion of VC0960, we first constructed a V. cholerae C6706 strain carrying a copy of VC0960 on the arabinoinducible vector pBAD18 [89], named pY in the main text. The deletion of VC0960 (chromosomal location 1,024,009–1,024,573) was performed in the presence of arabino in previously described [52].

The complementation plasmids expressing YbeY of various organisms were constructed by PCR amplification of each ybeY homolog from chromosomal DNA (i.e. b0659 of E. coli MG1655, VC0960 of V. cholerae C6706, PA3982 of P. aeruginosa PA01, SPR0869 of S. pneumoniae R6, and Rv2367c of M. tuberculosis H37v), and subsequently cloned into pHBR322 under control of the constitutive tetracycline promoter. DNA manipulations were performed according to the methods of Sambrook [90] and cloning products were sequence-verified.

Bacterial strains and growth conditions

The bacterial strains used for this work are V. cholerae wild-type C6706 [91], V. cholerae C6706 ΔybeY pY (this work), V. cholerae C6706 my-CTD::Tn [36], Mutant ID EC2413, Genomic locus 2.183.265), V. cholerae C6706 mg::Tn [36], Mutant ID EC13315, Genomic locus 445.329), V. cholerae C6706 no::Tn [36], Mutant
YbeY’s Functional Role in V. cholerae

Ribosome isolation and profiles

70 S ribosomes, and 50 S and 30 S subunits from V. cholerae C6706, V. cholerae YbeY pY mutant, V. cholerae rng::Tn mutant, V. cholerae rne-CTD::Tn mutant, V. cholerae rne::Tn mutant, E. coli MC4100, and E. coli YbeY mutant were isolated as described previously [93] with minor modifications. Briefly, log phase cultures (OD_{600} 0.5) grown in LB at 37°C were harvested, resuspended in ice-cold buffer A (20 mM HEPES pH 7.5, 50 mM NaCl, 10 mM MgCl₂, 5 mM β-mercaptoethanol, 0.1 mM PMSF), and lysed by French press (two passes at 11,000 psi). All subsequent steps were carried out at 4°C. Cell debris was removed by low speed centrifugation. The 30 S supernatant was obtained by two spins at 30,000 g for 30 min and was subsequently subjected to centrifugation at 100,000 g for 3 h. The final pellet containing the ribosomes was resuspended in buffer A and loaded onto a 10–40% sucrose gradient made in buffer A. After centrifugation at 150,000 g for 7 h, the 70 S ribosomes and ribosomal subunits were collected by monitoring the fractions spectro-photometrically (A_{260}).

Isolation and analysis of RNA

Total RNA from log phase cultures (OD_{600} 0.5) grown in LB at 37°C and rRNA from purified ribosome fractions were extracted using TRIzol (Ambion) according to the manufacturer’s protocol. Samples used for RT-qPCR and sRNA analysis were treated with TURBO DNase (Ambion) to remove any DNA contamination. Total rRNA profiles were analyzed by Synergel/agarose gel electrophoresis as described [94].

cDNA synthesis and RT-qPCR

cDNA was synthesized using the iScript cDNA Synthesis Kit (BioRad) according to the manufacturer’s protocol, and 1 µg of total RNA per 20 µl reaction. Relative expression levels were determined by RT-qPCR using the LightCycler 480 Real-time PCR system. Primers were designed using Primer Express 3.0 (optimal primer length of 20 bases, optimal amplicon length of 100 bases, GC-content of 50% and Tm of 50-60°C; see Table S1). 10 ng of cDNA and 0.2 µM of each primer was mixed with LightCycler 480 Cyper Green I master mix in a 20 µl reaction. PCR conditions were: a pre-incubation of 5 min at 95°C, an amplification stage of 45 cycles of 20 s at 95°C, 30 s at 57°C and 20 s at 72°C, and a melting curve stage of 5 s at 95°C, 1 min at 65°C increased to 97°C with steps of 2.2°C/s. All reactions were performed in triplicate and samples without reverse transcriptase were used as a control to assess genomic DNA contamination. The raw data was analyzed using LightCycler 480 Software (1.5.0 SP2), normalized against 5 S rRNA and the wild-type strain C6706 (without the pY maintenance plasmid; without additional carbon source) was used as calibrator condition. Relative gene expression was calculated using the Livak method [95].

Northern blot analysis of RNA

RNA was separated by denaturing polyacrylamide gel electrophoresis (6% polyacrylamide/7 M urea). The transfer of RNA onto Nytran membrane and Northern blot hybridization were as described in [96] with minor modifications. DNA oligonucleotides were end-labeled with 32P using T4 polynucleotide kinase (New England Biolabs). Prehybridizations were carried out at 42°C and hybridizations were carried out at 40°C–45°C. Following hybridization, membranes were washed at room temperature with 6×–2× SSC. Autoradiograms were analyzed by phosphorimager using a Typhoon scanner and ImageQuant software.

Mapping of 5’ and 3’ termini of rRNA

To map the 5’ termini of rRNA, primer extension assays were performed using Superscript II reverse transcriptase (Invitrogen). Typically, a 10 µl reaction contained 100 ng of total RNA or 25–50 ng of rRNA isolated from ribosomes, 100,000 cpm of the 32P-labeled DNA oligonucleotide and 2 µl of the 5’ reaction buffer (Invitrogen). After denaturation (65°C, 5 min), samples were chilled on ice for 5 min and then brought to room temperature for 5 min. 0.5 µl of DTT solution (Invitrogen), 0.25 µl of a 10 mM dNTP solution and 50 U of Superscript II (Invitrogen) were added. The reverse transcription reaction was carried out at 45°C for 20 min. The reaction was stopped by addition of loading dye containing formamide and heat denaturation. Reaction products were separated on denaturing polyacrylamide gels (6–10% polyacrylamide/7 M urea).

The 3’ termini of rRNA was mapped by site-specific RNase H cleavage assay as described by Deutscher and colleagues [29,97,98] with minor modifications, followed by Northern hybridization using probes specific for the mature 3’ termini of 16 S rRNA, 23 S rRNA or 5 S rRNA, respectively. Briefly, 100 ng of total RNA or 50 ng of rRNA isolated from ribosomes was mixed with a chimeric RNA/DNA oligonucleotide and 1 µl of 10× RNase H buffer (New England Biolabs) in a 10 µl reaction. After denaturation (95°C, 1 min), samples were brought to 65°C for 5 min, then 55°C for 15 min, 35°C for 15 min and then to room temperature for another 15 min to allow for formation of the DNA:RNA hybrid. 2.5 U of RNase H (New England Biolabs) was added. Samples were incubated for 60 min at 37°C. The reaction was stopped by addition of loading dye containing formamide and heat denaturation. Reaction products were separated on denaturing polyacrylamide gels (6–10% polyacrylamide/7 M urea) and analyzed by Northern blot hybridization.
Overexpression and purification of YbeY and RNase R

To construct the overexpression plasmid, ybeY of E. coli (b0659) and V. cholerae (VC0960) was cloned into pET28a under control of a T7 promoter with an N-terminal His-MBP-TEV(site)-tag. Purification of YbeY without RNase I contamination was accomplished by expression in BL21 (DE3) Arna [18]. To improve activity and yield, pET28a_YbeY was co-transformed with pGro7, a chaperone plasmid that encodes both GroES and GroEL under an arabinos inducible promoter [99]. MBP-YbeY was purified using amylose resin (New England Biolabs), the MBP-tag was cleaved by Turbo TEV protease (Eton Bioscience Inc.) and removed by size exclusion chromatography as described previously [18]. The purified YbeY protein was subjected to mass spectrometry to assess its purity.

R6 (pY_Sp).

To improve growth of E. coli V. cholerae ybeY (1–5 μM) cultures, grown overnight in LB medium and subsequently washed with 0.85% saline solution, onto LB plates containing various antibiotics or 0.1 mM H2O2 along with either 0.1% arabinose or 0.2% glucose as indicated. For UV survival, cultures of the V. cholerae strains were spotted onto LB plates and irradiated with a UV dose of 20 J/m^2 using a G15T8 UV lamp (GE) at 254 nm, then incubated in the dark. To determine heat sensitivity of C6706 Wt pY and YbeY pY cells from an early exponential culture supplemented with 0.2% glucose were incubated for 3 h at 37°C and 45°C before spotting as a dilution series onto LB plates supplemented with 0.2% glucose; plates were subsequently incubated for 18 h at 37°C. Cold sensitivity of C6706 Wt pY and YbeY pY mutant cells was resolved by spotting serially diluted cultures of a late exponential culture, grown in the presence of 0.1% arabinose, onto LB plates containing 0.2% glucose; plates were incubated for 2 days at 37°C and 18°C as indicated.

Similarly, complementation of the E. coli YbeY mutant by ybeY of various pathogens was determined by spotting serially diluted cultures (1:10, starting at OD600 0.1), grown overnight in LB medium, onto LB plates containing various antibiotics or 0.75 mM H2O2. A higher UV dose of 60 J/m^2 was used to measure UV resistance of the E. coli strains. Heat sensitivity of E. coli cells was determined by spotting serially diluted cultures of a late exponential culture onto LB plates; plates were incubated for 18 h at 45°C as indicated. The complementation vectors constitutively express ybeY of E. coli MC4100 (pY_Ec), V. cholerae N16961 (pY_Vc), P. aeruginosa H37Rv (pY_Pa), M. tuberculosis H37v (pY_Mt), or S. pneumoniae R6 (pY_Sp).

Bile-salt sensitivity of C6706 Wt pY and YbeY pY mutant was determined by growth in LB medium supplemented with 2.0% bile salt and 0.1% arabinose as specified. The number of colony forming units (CFU) was determined after 0, 1, 2, and 3 h of bile-salt treatment.

Pigment formation of C6706 Wt pY and YbeY pY mutant was determined by spinning down a similar number of cells grown to mid-log phase in LB medium containing 0.1% arabinose or 0.2% glucose as indicated.

Supporting Information

Figure S1 Growth analysis of V. cholerae ybeY. Growth curve of C6706 Wt pY and the ΔybeY pY strain in LB medium at 37°C. The Wt and mutant strains were grown in medium supplemented with arabinose (Ara+). The ΔybeY pY strain was diluted into medium lacking arabinose (Ara−) for depletion of YbeY, grown to saturation and then subcultured a second time into fresh medium lacking arabinose (Ara−/Ara−). (TIF)

Figure S2 Analysis of 23 S rRNA and 5 S rRNA in V. cholerae ΔybeY. Mapping of 5′ and 3′ (termini of A) 23 RNA
and B) 5 S rRNA from C6706 Wt pY and the ΔybeY pY strain. “F” and “M” specify the positions of bands derived from the precursor and mature forms of 23 S rRNA and 5 S rRNA. “pY” indicates that ybeY is expressed from a plasmid. Ara+, cells were grown in LB in the presence of arabinose. Gluc+, cells were grown in LB in the presence of glucose. Ara+/Gluc+, intermediate YbeY depletion by switching the carbon source of the ΔybeY pY strain in early exponential phase from arabinose to glucose (for details see Materials and Methods).

**Figure S3** Analysis of *V. cholerae* YbeY’s in vitro RNase activity. A) Total RNA (250 ng) isolated from *V. cholerae* can be degraded by purified YbeY of *V. cholerae* (10 μM), similar to *E. coli* YbeY (5 μM). EDTA (50 mM) inhibits YbeY’s RNase activity. RNA was analyzed by agarose gel electrophoresis. The positions of the 23 S and 16 S rRNA are indicated. B-C) Purified YbeY of *V. cholerae* (1–5 μM) shows endoribonuclease activity on 5′-labeled oligoribonucleotides (0.03 μM); hairpin substrate in B) and ssRNA in C). Digestion products were analyzed by polyacrylamide gel electrophoresis. D) In vitro ribosome quality control by *V. cholerae* (V) and *E. coli* (Ec) YbeY together with RNase R. 70 S ribosomes of C6706 Wt pY grown in the presence of arabinose (Ara+) were incubated with YbeY, RNase R, or a mixture of YbeY and RNase R from *E. coli* or *V. cholerae* as indicated. The positions of 23 S and 16 S rRNAs are indicated based on their mobility.

**Figure S4** Ribosome profiles of *V. cholerae* mutant strains with transposon insertions in genes encoding RNase E (*rne-CTD::Tn*), RNase G (*rng::Tn*) or RNase R (*rnr::Tn*). Analysis of ribosome profiles in C6706 Wt pY Wt. ΔybeY pY (∆ybeY pY (Δ)), *rne-CTD::Tn* (E), *rng::Tn* (G) and *rnr::Tn* (R). Wt pY and ΔybeY pY cells were first grown in LB medium supplemented with arabinose and then subcultured into glucose-containing medium for depletion of YbeY; all other strains were grown in LB medium without additional carbon source. Polysomes, 70 S, 50 S and 30 S ribosomes are indicated.

**Table S1** Oligonucleotides used in this study.

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**Author Contributions**

Conceived and designed the experiments: MV CK BWD MFFA JIM ULR GCW. Performed the experiments: MV CK BWD MFFA. Analyzed the data: MV CK BWD MFFA. Contributed reagents/materials/analysis tools: MV CK BWD MFFA JIM ULR GCW. Wrote the paper: MV CK ULR GCW.

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**Figure S5** YbeY is highly conserved among bacteria. Sequence alignment of YbeY proteins from *E. coli* MG1655 (Ec), *V. cholerae* N16961 (Vc), *P. aeruginosa* PAO1 (Pa), *M. tuberculosis* H37Rv (Mt), and *S. pneumoniae* R6 (Sp). The highly conserved H3XH5XH motif in the catalytic pocket is indicated.
Haemophilus influenzae

Escherichia coli


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