The oxidative stress response and virulence of pathogenic *Leptospira* are controlled by the interplay of two peroxide stress regulators.

Short title: Identification of a second PerR-like regulator in pathogenic *Leptospira*.

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Abstract

Pathogenic *Leptospira* are the causative agents of leptospirosis, the most widespread zoonotic infectious disease. Leptospirosis is a potentially severe and life-threatening emerging disease with highest burden in sub-tropical areas and impoverish populations. Mechanisms allowing pathogenic *Leptospira* to survive inside a host and induce acute leptospirosis are not fully understood. The ability to resist deadly oxidants produced by the host during infection is pivotal for *Leptospira* virulence. We have previously shown that genes encoding defenses against oxidants in *L. interrogans* are repressed by PerRA (encoded by LIMLP_10155), a peroxide stress regulator of the Fur family. In this study, we describe the identification and characterization of another putative PerR-like regulator (LIMLP_05620) in *L. interrogans*. Protein sequence and phylogenetic analyses indicated that LIMLP_05620 displayed all the canonical PerR amino acid residues and is restricted to pathogenic *Leptospira* clades. We therefore named this PerR-like regulator PerRB. In *L. interrogans*, the PerRB regulon is distinct from that of PerRA. While a *perRA* mutant had a greater tolerance to peroxide, inactivating *perRB* led to a higher tolerance to superoxide, suggesting that these two regulators have a distinct function in the adaptation of *L. interrogans* to oxidative stress. The concomitant inactivation of *perRA* and *perRB* resulted in a higher tolerance to both peroxide and superoxide and, unlike the single mutants, to the loss of *Leptospira* virulence. Interestingly, this correlated with major changes in gene and non-coding RNA expression, only observed in the double *perRAperRB* mutant. Notably, several virulence-associated genes (*clpB, ligA/B*, and *lvrAB*) were repressed. By obtaining the first double mutant in a pathogenic
Leptospira strain, our study has uncovered for the first time the interplay of two PerRs, not only in the adaptation of Leptospira to oxidative stress, but also in their virulence and pathogenicity, most likely through the transcriptional control of a complex regulatory network.

Author summary

Leptospirosis is a widespread infectious disease responsible for over one million of severe cases and 60,000 fatalities annually worldwide. This neglected and emerging disease has a worldwide distribution, but it mostly affects populations from developing countries in sub-tropical areas. The causative agents of leptospirosis are pathogenic bacterial Leptospira spp. There is a considerable deficit in our knowledge of these atypical bacteria, including their virulence mechanisms. In addition to the Leptospira PerRA regulator that represses defenses against peroxide, we have identified and characterized a second PerR regulator in pathogenic Leptospira species (PerRB) that participates in Leptospira tolerance to superoxide. Phenotypic and transcriptomic analyses of single PerRA and PerRB mutants suggest that the two PerRs fulfill distinct functions in the adaptation to oxidative stress. However, concomitant inactivation of PerRA and PerRB resulted in a higher tolerance to both peroxide and superoxide, but to a loss virulence.

The absence of the two PerR regulators resulted in global and major changes in the transcriptional profile, including a dramatic decrease of several virulence factor expression. Our study has demonstrated that PerRA and PerRB cooperate to orchestrate a complex regulatory network involved in Leptospira virulence.
Introduction

Pathogenic *Leptospira* spp. are aerobic Gram-negative bacteria of the spirochetal phylum that are the causative agents of leptospirosis, the most widespread zoonosis [1]. More than one million cases of leptospirosis are currently reported annually in the world, with 10% of mortality [2]. This disease is considered as a health threat among impoverished populations in developing countries under tropical areas [2], but the number of reported cases of leptospirosis are also on the rise in developed countries under temperate climates [3]. Rodents are asymptomatic reservoir for leptospires as the bacteria colonize the proximal renal tubules of these animals. Leptospires are shed in the environment through the urine of infected animals and leptospirosis is transmitted to other animal species and humans mostly by exposure to contaminated soils and water. *Leptospira* penetrate an organism through abraded skins and mucous membranes, subsequently disseminate within the bloodstream and rapidly spread to multiple tissues and organs (including kidney, liver, lungs). Clinical manifestations range from a mild flu-like febrile state to more severe and fatal cases leading to hemorrhages and multiple organ failure. Because of the lack of efficient tools for genetic manipulation of *Leptospira* spp. and their fastidious growth in the laboratory conditions, our understanding of the mechanism of pathogenicity and virulence as well as the basic biology of these pathogens have been greatly hampered [4,5].

During their life cycle, most bacteria will be exposed to reactive oxidative species (ROS), such as superoxide anion (‘O$_2^-$’) and hydrogen peroxide (H$_2$O$_2$), that are produced endogenously or encountered in the environment [6]. The superoxide is formed during the aerobic respiratory chain upon the reduction of the dioxide (O$_2$). Dismutation of superoxide will give rise to H$_2$O$_2$ which, in turn, can react with ferrous iron to generate the highly reactive hydroxyl radicals (‘OH) through the Fenton reaction. These ROS are also produced
together with hypochlorous acid (HOCl), and nitric oxide anion (•NO) as powerful and
efficient weapons by eukaryotic innate immune response upon infection by pathogenic
bacteria [7]. ROS cause oxidative damage to cellular components (proteins, DNA and lipids)
and this would result in bacterial death if bacteria had not developed scavenging enzymes to
counteract the deadly effect of ROS, including catalase, peroxidases and superoxide
dismutase or reductase (SOD, SOR). Indeed, in response to any increase in ROS
concentration, as occurred during environmental oxidative stress or when infecting a host,
bacteria trigger an adaptive response allowing the fine-tuning of scavenging enzyme synthesis
rate that appropriately adapts the defenses against ROS to the oxidant assault. ROS
production is increased upon infection by *Leptospira* [8] and with the development of severe
leptospirosis in patients and infected animals [9,10]. In fact, the ability to detoxify H$_2$O$_2$ is
essential for *Leptospira* virulence as inactivation of the catalase-encoding gene led to
The oxidative stress adaptive response in bacteria is controlled by specialized ROS sensing
transcription factors. OxyR and PerR are the main peroxide-sensing regulators found in
Gram-negative and Gram-positive bacteria, respectively [12]. OxyR and PerR are functional
equivalents but they do control expression of peroxide scavenging enzymes by different
mechanisms. OxyR is a transcriptional regulator from the LysR family. Tetrameric OxyR
binds promoters and activates the expression of genes coding for catalase and peroxidases
through the oxidation of its H$_2$O$_2$ sensing cysteine residue [13,14]. PerR belongs to the Fur
(Ferric uptake regulator) transcriptional factor family. It is a metalloprotein that binds DNA in
the presence of iron or manganese and represses the expression of catalase and peroxidases
[15–17]. In the presence of peroxide, PerR is oxidized on the histidine residues participating
in iron coordination, PerR dissociates from DNA and peroxide-scavenging enzyme repression
is alleviated [18,19]. In Gram-negative bacteria, SOD expression is controlled by the SoxRS
system [20,21] by a redox-sensing mechanism and oxidation of a Fe-S cluster [22]. In Gram-
positive bacteria, SOD expression regulation probably involves the alternative Sigma Factor
SigB among other mechanisms [23]. Pathogenic *Leptospira* spp. are among the few examples
of Gram-negative bacteria where the expression of peroxide-scavenging enzymes is regulated
by a PerR (encoded by LIMLP_10155/LIC12034/LA1857) and not an OxyR [24]. Moreover,
their genomes do not contain any ORF encoding a SOD and they do not exhibit canonical
SOD activity [25,26].

We have very recently characterized the transcriptional response to hydrogen peroxide in the
pathogen *L. interrogans* and shown that these bacteria respond to sublethal H$_2$O$_2$
concentration by increasing the expression of catalase and of two peroxidases
(Alkylperoxiredoxin (AhpC) and Cytochrome C peroxidase (CCP)) [27]. When *Leptospira*
were exposed to deadly H$_2$O$_2$ concentration, additional enzymes with a putative role as
antioxidants and/or in repair of oxidized cysteines in proteins were up-regulated, including
several thiol oxidoreductases (thioredoxin, glutaredoxin, DsbD, and Bcp-like proteins) [27].
Several genes of the LexA regulon (*recA*, *recN*, *dinP*) and other genes with putative role in
DNA repair (*mutS*, *radC*) had a higher expression as well as genes encoding for canonical
chaperones (*dnaK/dnaJgrpE*, *groES/EL*, and *hsp15/20*) [27]. Only genes coding for the
catalase and peroxidases were under the control of PerR and our study has revealed a complex
regulatory network independent of PerR involving other transcriptional regulators, sigma
factors, two component systems and non-coding RNAs [27]. During the course of this study,
we noticed that an ORF encoding a Fur-like regulator (LIMLP_05620/LIC11158/LA2887)
was up-regulated when *Leptospira* were exposed to a deadly concentration of H$_2$O$_2$. Here, we
report the functional characterization of this pathogenic *Leptospira*-specific Fur-like regulator
in the adaptation of *Leptospira* to oxidative stress. Phenotypic analyses of a mutant
inactivated in LIMLP_05620 indicates a role of this Fur-like regulator in *Leptospira* tolerance.
to superoxide. This, together with the presence of the canonical amino acid residues of the PerR DNA binding helix and H$_2$O$_2$ sensitivity, strongly suggest that LIMLP_05620 encodes a second PerR-like regulator in pathogenic *Leptospira* species. By obtaining a double mutant where LIMLP_05620 and *perR* (LIMLP_10155) are concomitantly inactivated, we have also investigated the interplay between these two PerR-like regulators in the adaptation to oxidative stress and virulence of *L. interrogans*. We have demonstrated a cooperation of LIMLP_05620 with PerR in controlling several *Leptospira* virulence-associated genes, including *ligA*, *ligB*, *lvrAB*, and *clpB*, perhaps illustrating the importance of functional redundancy in pathogenic *Leptospira* virulence and pathogenicity.
Results

Identification of an ORF that encodes a novel putative PerR regulator in pathogenic Leptospira species.

Regulators of the Fur family are homodimeric metalloproteins with a two-domain organization composed of an amino-terminal DNA binding domain and a carboxy-terminal dimerization domain (Fig 1A). The DNA binding domain contains a winged helix-turn-helix (HTH) DNA binding motif (H2-H4, in Fig 1A) where DNA binding is mediated by the H4 helix. The dimerization domain consists of an $\alpha/\beta$ domain. The regulatory iron that controls DNA binding and dissociation is coordinated by histidine, aspartate, and glutamate residues located in a loop at the hinge of the amino and carboxy-terminal domains. Most of Fur-like regulators also coordinate a structural metal (zinc) through 2 cysteinate motifs (CxxC, where x designates any AA). This structural metal allows correct folding and dimeric assembly of the regulator.

Due to a great conservation in protein folding, metal coordination and similarity in the metal-induced conformational switch controlling DNA binding, it is difficult to distinguish members of the Fur family on the sole basis of their primary sequence. However, in B. subtilis, a single amino acid residue in the H4 helix of the amino-terminal DNA binding domain (N61 and R61 for B. subtilis PerR and Fur, respectively) allows PerR and Fur to discriminate between their respective DNA sequence targets (PerR and Fur boxes, respectively) [28] (Fig 1B). In addition, D104 residue in the carboxy-terminal domain is pivotal in the PerR sensitivity to H$_2$O$_2$. The corresponding residue in Fur is a glutamate and mutating this residue in aspartate leads to H$_2$O$_2$ sensitivity [29] (Fig 1B). Therefore, N61 and D104 both allow to differentiate a PerR from a Fur in B. subtilis and the presence of these
canonical amino acid residues in PerR sequences is well-conserved in other bacterial species [28,29].

*L. interrogans* genome encodes 4 ORFs that share homology with regulators of the Fur family. Among those *Leptospira* Fur-like regulators, LIMLP_10155 is the only *Leptospira* Fur-like regulator that is functionally and structurally characterized. It encodes a PerR that represses genes encoding defenses against peroxide, including catalase and other peroxidases [24,27,30]. Our previous structural characterization of the PerR from *L. interrogans* indicates that this member of the Fur family lacks a structural metal binding site despite a correct folding and functional dimeric assembly [30].

Sequence alignment of these ORFs with the Fur and PerR from *B. subtilis* shows a good conservation of the two-domain organization and residues involved in the regulatory metal coordination (Fig 1B). Interestingly, two of the 4 Fur-like ORFs of *L. interrogans*, LIMLP_10155 (LIC12034/LA1857 encoding a PerR) and LIMLP_05620 (LIC11158/LA2887), exhibit the canonical asparagine (N60 and N68, respectively) and aspartate (D103 and D112, respectively) residues of a typical PerR. The third ORF encoding a putative Fur-like regulator, LIMLP_04825 (LIC11006/LA3094), possesses the two Fur typical residues, R76 and E121, respectively. The fourth ORF encoding a putative Fur-like regulator, LIMLP_18590 (LIC20147/LB183) possesses the typical Fur arginine residue in its putative H4 DNA binding helix (R51) but a typical PerR aspartate residue in the carboxy-terminal domain (D94). Of note, LIMLP_18590 has a glutamate residue at the position 96.

Fold prediction suggests that the three Fur regulators encoded by LIMLP_05620, LIMLP_04825 and LIMLP_18590 adopt the two-domain organization typical of the Fur family depicted in the crystal structure of LIMLP_10155 (Fig 1C).

The closest relative of the PerR-encoding LIMLP_10155 is LIMLP_05620 with about 26% of sequence identity, and LIMLP_04825 and LIMLP_18590 are closest relatives that share 20%
of sequence identity. LIMLP_05620 shares about 27% identity with the well-characterized \textit{B. subtilis} PerR. The putative H4 helix in LIMLP_05620 (Leu63-Ser75) is relatively well conserved with that of \textit{B. subtilis} (Val56-Ser69) (Fig 1B-C) and LIMLP_05620 displays a typical regulatory metal coordination site (His44-Asp93-His99-His101-Asp112). As the LIMLP_10155-encoded PerR, LIMLP_05620 lacks the cysteinate motif involved in structural metal coordination [30] (Fig 1B). On the contrary, both LIMLP_04825 and LIMLP_18590 have one or two cysteinate motifs for structural metal coordination ($C_{113}xxC_{116}$ and $C_{86}xxC_{89}-C_{122}xxC_{125}$, respectively). Therefore, LIMLP_05620 encodes a putative PerR-like regulator closely related to the PerR-encoding LIMLP_10155 whereas LIMLP_04825 and LIMLP_18590 could encode other type of Fur-like regulators (Fur, Zur, or Nur). We therefore annotated the LIMLP_10155 and LIMLP_05620 ORFs as \textit{perRA} and \textit{perRB}, respectively.

**Phylogenetic analysis of PerRA and PerRB in \textit{Leptospira} species.**

To get a better understanding of the evolutionary relationship of the four Fur-like regulators in pathogenic \textit{Leptospira}, we undertook phylogenetic analyses by searching for homologous sequences of the LIMLP_10155, LIMLP_05620, LIMLP_18590 and LIMLP_04825 proteins among the representative genomes present in GenBank. This revealed a large phylogenetic distribution with several branches (Fig 2A). The sequences homologous to the LIMLP_04825 and LIMLP_18590 proteins form two distinct groups (red and orange, respectively) separated by a common ancestor. To get better definition of phylogenetic relationships of PerR-like homologues, we performed analysis with only a subset of sequence (Fig 2B). This phylogenetic analysis shows two separated groups composed of the sequences of LIMLP_10155 (PerRA) and LIMLP_05620 (PerRB) (see S1Fig for a more complete and detailed tree).
The sequences of LIMLP_10155 and LIMLP_05620 ORFs from the strain L. interrogans serovar Manilae were searched and compared in all available genomes from the Leptospira genus (S1 Table). As seen in Fig 3, LIMLP_10155 is present in the saprophytes S1 and S2 clades and in the P1 clade (highly virulent strains). This ORF is absent from most of the P2 clade (intermediate strains). However, there are two exceptions in the P2 clade species since homologues of LIMLP_10155, which might have been acquired by a recent horizontal gene transfer, are present in L. dzoumognesis and L. wolffii. Additionally, this ORF is also present in other bacteria from the order Leptospirales such as Turneriella parva and Leptonema illini (Fig 2B). This suggests that LIMLP_10155 (PerRA) was present in Leptospirales ancestor before Leptospira divergence and lost in the P2 clade. On the other side, LIMLP_05620 ORF is only present in P1 and P2 clades and absent in all species from S1 and S2 clades (Fig 3). LIMLP_05620 is also not found in other bacteria from the Leptospirales order (Fig 2B and S1 Fig). This restricted distribution suggests that the ancestor of pathogenic strains (P1 and P2 clades) has likely acquired LIMLP_05620 after their divergence with other Leptospira. Overall, both PerR-encoding LIMLP_10155 and LIMLP_05620 ORFs only coexist in P1 clade that comprises the highly virulent Leptospira species. Altogether, these findings indicate that pathogenic Leptospira strains encode a second putative PerR-like regulator that is absent in saprophytes.

Role of PerRB in L. interrogans tolerance to ROS.

As demonstrated previously [27], when L. interrogans are exposed to a sublethal dose of H₂O₂ (10 µM for 30 min) perRA expression is increased by a 7-fold whereas that of perRB is unchanged (Fig 4). In the presence of a higher dose of H₂O₂ (1 mM for 1h), expression of both perRA and perRB was increased significantly by a 6-fold (Fig 4). This suggests that PerRB, like PerRA, responds to deadly H₂O₂ dose.
We have previously shown that inactivating *perRA* led to the derepression of *katE, ahpC* and *ccp* and to a higher tolerance to H$_2$O$_2$ [27,30] (see S2 Fig). The *perRA* mutant exhibited a reduced ability to grow in the presence of the superoxide-generating compound paraquat [30]. A mutant with a transposon inserted into the PerRB-encoding LIMLP_05620 ORF was available in our random transposon mutant library and was used to investigate *L. interrogans* tolerance of ROS in the absence of PerRB. When cultivated in EMJH medium, the *perRB* mutant did not reach the same density than the WT strain at stationary phase (Fig 5A and S2 Fig). Inactivating *perRB* did not have any effect on the ability of *L. interrogans* to tolerate deadly concentration of H$_2$O$_2$ (S2 Fig); however, it increases the capability of *Leptospira* to grow in the presence of paraquat (Fig 5B). Complementing in trans the *perRB* mutant restored the WT strain phenotype in the absence of paraquat (Fig 5A) and it decreased the growth rate of the cells to a somehow lower level than that of the WT in the presence of paraquat (Fig 5B). This indicates that PerRB is involved in *Leptospira* tolerance to superoxide, very likely by repressing (directly or indirectly) defenses against this ROS. Therefore, PerRA and PerRB have distinct function in pathogenic *Leptospira* survival in the presence of oxidants.

**Identification of differentially-expressed genes upon *perRB* inactivation.**

To understand the role of PerRB in *L. interrogans* tolerance to ROS, we compared the global transcriptional profiles of the *perRB* mutant and WT strains. Differential gene expression analysis revealed changes in the transcription of 123 genes, with 59 and 64 down- and up-regulated, respectively (see S2 Table for a complete set of data). However, *perRB* inactivation did not lead to dramatic changes in gene expression as the majority of Log$_2$FC (108 out of 123) ranged between -1 and 1 (S2 Table). These findings indicate that the absence of an active PerRB did not lead to substantial significant changes in genes expression when
Leptospira are cultivated in the laboratory conditions (in EMJH medium at 30°C) and during the exponential phase. Nevertheless, when examining the nature of the highest differentially-expressed genes in the perRB mutant, some tendencies could be observed. Many of the differentially-expressed ORFs were annotated as protein with unknown function and did not have homologs in the saprophyte L. biflexa strain (S2 Table and Table 1).
<table>
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<tr>
<th>ORF ID*</th>
<th>Gene</th>
<th>L. biflexa*</th>
<th>Function</th>
<th>Log2FC</th>
<th>Adjusted p-value</th>
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<td>LIMLP_02490* (LIC12988/LA0587)</td>
<td>LEPBI_I0886</td>
<td>Lipase putative extracellular lipoprotein</td>
<td>-1.608</td>
<td>6.11e-04</td>
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<td>6.96e-03</td>
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<td>LIMLP_13165** (LIC12631/LA1029)</td>
<td>sph2</td>
<td>LEPBI_I2540</td>
<td>DNA-binding stress protein Dps</td>
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<td>LIMLP_16695 (LEPIC3326/LA4096)</td>
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**Down-regulated genes**

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<th>ORF ID*</th>
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<th>Function</th>
<th>Log2FC</th>
<th>Adjusted p-value</th>
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<td>LIMLP_02880* (LIC12912/LA0688)</td>
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<td>CRISPR-associated protein Cas5</td>
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<td>LIMLP_02885* (LIC12911-12910/LA0689-0690)</td>
<td>cas3</td>
<td>CRISPR-associated protein Cas3</td>
<td>0.834</td>
<td>4.51e-03</td>
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<td>LIMLP_04075** (LIC12680/LA0974)</td>
<td>Adhesin/FimH-like protein/Duf1566 domain</td>
<td>1.110</td>
<td>4.29e-03</td>
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<td>LIMLP_05455** (LIC11126/LA2932)</td>
<td>Diguanylate cyclase</td>
<td>0.983</td>
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<td>LIMLP_05845 (LIC11203/LA2827)</td>
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<td>hemN</td>
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<td>LIMLP_18755 (LIC20176/LB225)</td>
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<td>LIMLP_19320* (LA1770)</td>
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**Up-regulated genes**
Table 1. Differentially-expressed ORFs upon *perRB* inactivation

Selected up-and down-regulated genes in the LIMLP_05620 (*perRB*) mutant with an adjusted p-value cutoff of 0.05.

* Gene numbering is according to Satou et al [31]. Corresponding genes of *L. interrogans* serovar Lai strain 56601 and serovar Copenhageni Fiocruz strain L1-130 are indicated in parenthesis.

* Closest ortholog in the saprophytes *L. biflexa* serovar Patoc strain Patoc1. The absence of syntheny is indicated in italic.

Genes that are down-regulated upon *perRA* inactivation as determined previously [27] are indicated in bold.

Down (*) and up (**) -regulated genes upon exposure to lethal H$_2$O$_2$ dose as determined previously [27].
Among the highest up-regulated genes, two ORFs (LIMLP_04075 and LIMLP_18760) encoded lipoproteins with a putative adhesin function. These proteins contain DUF1566 domain repeats which is also shared by Lsa25, a Leptospiral surface adhesin that binds extracellular matrix (ECM) [32].

Several genes involved in the metabolism of c-di GMP were differentially-expressed upon *perRB* inactivation. C-di GMP is a secondary messenger in bacteria that regulates a variety of processes such as biofilm formation, motility, stress adaptation, and virulence. C-di GMP synthesis is catalyzed by diguanylate cyclases (DGCs) whereas its hydrolysis is catalyzed by phosphodiesterases (PDEs). DGCs and PDEs are numerous in pathogenic *Leptospira*, suggesting that c-di GMP fulfills an important role in sensing environmental signals when *Leptospira* infect and colonize a host. C-di GMP has been recently shown to regulate biofilm formation, motility and protection against environmental stress in pathogenic *Leptospira* [33].

Four DGCs (LIMLP_05450, LIMLP_05455, LIMLP_05460, LIMLP_05485) were up-regulated upon *perRB* inactivation (Table 1). These DGC-encoding ORFs are located in a gene cluster (LIMLP_05485-05450) that contains 7 ORFs coding for DGCs. LIMLP_05450, LIMLP_05455, LIMLP_05460, and LIMLP_05485 display the typical diguanylate cyclase GGDEF and sensory PAS domains. A DGC activity was demonstrated *in vitro* for LIMLP_05450, LIMLP_05455, LIMLP_05460 [34]. Three PDE-encoding ORFs (LIMLP_05845, LIMLP_9580, and LIMLP_18375) were also up-regulated in the *perRB* mutant.

LIMLP_13165 was among the most down-regulated ORFs when *perRB* was inactivated. It encodes a secreted protein with sphingomyelinase C and hemolytic activities [35]. Another significantly down-regulated ORF encoded a protein with an acyl CoA acetyl transferase domain annotated as a putative hemolysin (LIMLP_15470). This ORF is up-regulated when *L. interrogans* is cultivated in DMC implemented in rats [36].
An ORF encoding an AraC transcriptional regulator (LIMLP_19320), and two ORFs of unknown function (LIMLP_18755 and 19325) were among the most up-regulated. The orthologs of LIMLP_19320 and LIMLP_19325 in L. interrogans serovar Lai belongs to a genomic island (Lai GI B, LA1747-1851) that can excise from the chromosome and form an independent replicative plasmid [37,38].

Among the down-regulated genes, several ORFs encode factors related to oxidative stress. LIMLP_04255 is part of a gene cluster (LIMLP_04240-04285) which code for a putative TonB-dependent transport system repressed by PerRA. We have previously shown that some genes of this cluster (LIMLP_04245, LIMLP_04270 and LIMLP_04280) are involved in L. interrogans tolerance to superoxide [27]. LIMLP_11400 encodes the DNA repair protein RadC and LIMLP_14715 is a homolog of the E. coli Dps, a protein that sequesters iron and protects DNA from oxidative damage. LIMLP_06190 encodes a putative disulfide oxidoreductase with the N-terminal ScdA domain (DUF1858). In S. aureus, ScdA is a di-iron protein involved in repair of oxidatively damaged iron-sulfur cluster proteins [39]. LIMLP_14595 encodes a putative transmembrane lipoprotein with a cytochrome-like domain that shows homology with the CcoP subunit of the cytochrome C oxidase and could function in the respiratory chain or be an enzyme cofactor.

Only 7 out of the 123 differentially-expressed genes in the perRB mutant were also differentially-expressed upon perRA inactivation with a similar inclination (S3 Fig) [27]. LIMLP_02010 and LIMLP_04325 were up-regulated whereas LIMLP_04255, LIMLP_11810, LIMLP_14225, LIMLP_15470 and LIMLP_18235 were down-regulated in the two mutants.

Notably, 82 out of the 123 differentially-expressed ORFs in the perRB mutant were also differentially-expressed upon exposure of L. interrogans to H$_2$O$_2$ (S3 Fig) [27]. Thus, 66% of the PerRB regulon is also regulated by the presence of H$_2$O$_2$. Interestingly, the majority of
ORFs down-regulated in the perRB mutant, including the RadC and the Dps-encoding ORFs, were up-regulated in the presence of H$_2$O$_2$ (with Log$_2$FCs of 3.46 and 1.10, respectively) (S3 Fig and Table 1). On the contrary, many up-regulated ORFs in the perRB mutant had a lower expression in the presence of H$_2$O$_2$. For instance, the ORFs that code for Cas5 (LIMLP_02880), Cas3 (LIMLP_02885), and two DGCs (LIMLP_05450 and LIMLP_05455) were down-regulated upon exposure to H$_2$O$_2$ with Log$_2$FCs lower than -1.21 (S3 Fig and Table 1).

Concomitant inactivation of perRA and perRB leads to a higher resistance to ROS but to a lower virulence

In order to investigate whether PerRA and PerRB cooperate in regulating the adaptive response to ROS, we inactivated perRA by allelic exchange in the perRB mutant (S4 Fig). This allowed obtaining a double perRAperRB mutant in a L. interrogans strain, the first double mutant constructed in a pathogenic Leptospira.

The double perRAperRB mutant had a growth rate comparable to that of the single perRA and perRB mutants and WT strains when L. interrogans were cultivated in EMJH medium (Fig 6A). However, entry in exponential phase was delayed if the culture medium was inoculated with stationary phase-adapted perRAperRB mutant (S5 Fig). We had already shown that a perRA mutant had a higher ability to grow and survive in the presence of deadly concentration of H$_2$O$_2$ but a slower growth in the presence of the superoxide-generating paraquat ([30], and see in S2 Fig and Figs 6B and 6C). On the contrary, inactivating perRB leads to a higher resistance to paraquat (Fig 5 and Fig 6C). The concomitant inactivation of perRA and perRB led to a greater growth in the presence of both H$_2$O$_2$ (Fig 6B) and paraquat (Fig 6C). To complement the double perRAperRB mutant strain, the PerRB-encoding ORF LIMLP_05620 was expressed in trans using the replicative pMaORIgenta vector (S4 Fig). The growth of the
trans-complemented perRAperRB mutant resumed to an impaired growth, as that of the WT and single perRA mutant strains, in the presence of paraquat (Fig 6D). Therefore, the double perRAperRB mutant exhibited cumulative phenotypes of the respective single perRA and perRB mutants when L. interrogans are cultivated in the presence of ROS.

We then tested whether perRA and perRB inactivation had any influence on L. interrogans virulence in the animal model of acute leptospirosis. All hamsters infected intraperitoneally with $10^4$ bacteria of the perRA or perRB single mutant strains exhibited morbidity sign after 7-8 days (Fig 6E), similarly to the WT strain. In contrast, all animals infected intraperitoneally with $10^4$ bacteria of the double perRAperRB mutant strain did not show any sign of morbidity three weeks post-infection (Fig 6E), even when the animals were infected with $10^6$ bacteria of the double perRAperRB mutant strain (Fig 6F). Virulence was restored in the double perRAperRB mutant strain complemented in trans only with perRB (Fig 6F).

Therefore, the concomitant inactivation of perRA and perRB resulted in a loss of virulence in L. interrogans and expressing only perRB in the double mutant restored Leptospira virulence. Altogether, these results demonstrate that despite a higher resistance to ROS, the double perRAperRB mutant exhibited a dramatically reduced virulence.

Concomitant inactivation of perRA and perRB has a pleiotropic effect in L. interrogans gene expression.

To further understand the interplay between PerRA and PerRB in controlling the oxidative stress response and virulence in L. interrogans, we performed RNA-Seq experiments on the double perRAperRB mutant and compared its transcriptomic profile with that of WT and single perRA and perRB mutant strains. 949 and 1024 ORFs were down- and up-regulated, respectively, in the double perRAperRB mutant (Fig 7A and see S3 Table for a complete set of data). Therefore,
concomitant perRA and perRB inactivation resulted in differential expression of almost half of the total coding sequences of L. interrogans; in comparison, only about 1% and 3% of the total coding sequences of L. interrogans were differentially-expressed in the single perRA and perRB mutants, respectively (S2 Table) [27]. Volcano scatter plot representation indicated not only a higher magnitude of fold changes but also a greater statistical significance in the double perRAperRB mutant (Fig 7B-D).

Most of the differentially-expressed ORFs in the perRA mutant were also differentially-expressed in the double perRAperRB mutant (Fig 7A). Many genes of the LIMLP_04240-04280 cluster encoding a putative TonB-dependent transport system, the two-component system VicKR (LIMLP_16720-16725), a putative hemolysin (LIMLP_15470) and several ORFs of unknown function (from LIMLP_14190 to LIMLP_14225) were down-regulated in the perRA [24,27] and perRAperRB mutants (Fig 7 and 8A, S4 Table). Likewise, the ORFs encoding the catalase, AhpC and CCP (LIMLP_10145, LIMLP_05955 and LIMLP_02795, respectively), that are repressed by PerRA and up-regulated in the single perRA mutant [24,27], were also up-regulated in the double perRAperRB mutant (Fig 7 and 8B, S5 Table).

21 and 27 ORFs that are respectively down- and up-regulated in the perRB mutant were also down- and up-regulated in the perRAperRB mutant (Fig 7A). LIMLP_11400 (encoding RadC), LIMLP_04255, encoding ExbB of the TonB-dependent transport system, the hemolysin-encoding ORF LIMLP_15470, and LIMLP_15890 were down-regulated in the single perRB and double perRAperRB mutants (Fig 7 and S2-S4 Tables).

Interestingly, the vast majority of the differentially-expressed ORFs in the double perRAperRB mutant did not exhibit any change in their expression in the single perRA and perRB mutants. For instance, of the DGCs and PDEs that were up-regulated in the perRB mutant, only LIMLP_09580 was up-regulated in the double perRAperRB mutant (S2, S3 and S5 Tables). In fact, the perRAperRB double mutant exhibited a distinct expression pattern of
genes involved in signaling (Fig 8C). The LIMLP_07050 ORF that codes for a DGC was
down-regulated; two ORFs encoding adenylate/guanylate cyclases (LIMLP_00130 and
LIMLP_02085) and the PDE-encoding LIMLP_04775 ORF were up-regulated in the
perRAperRB mutant. Finally, only 6 ORFs were differentially expressed in all mutants (Fig
7A), including LIMLP_04255 and LIMLP_15470 (S4 and S5 Tables). Moreover, a
substantial number of regulatory factors (transcriptional regulators, two-component systems,
sigma factors) were differentially-expressed exclusively in the perRAperRB mutant (S4 and
S5 Tables).

In the double perRAperRB mutant, several ORFs encoding factors putatively involved in cell
growth (cell division, respiration and cell wall homeostasis), chemotaxis and motility are
significantly up-regulated, with a Log₂FC greater than 1.5 (S5 Table). This correlates with a
higher ability of the perRAperRB mutant to reach a higher cell number when cultivated in
vitro at 30°C (Fig 6 and S4 Fig).

In addition to the PerRA-repressed peroxidases (catalase, AhpC, CCP), other oxidative-stress
related factors exhibited a higher expression in the perRAperRB mutant (Fig 8B). DoxX-
encoding ORF, which is up-regulated upon concomitant perRA and perRB inactivation
(Log₂FC 1.65), is an integral membrane protein that interacts with SodA in M. tuberculosis
and participates in tolerance to oxidative and redox stress [40]. Two imelysins
(LIMLP_14170/LruB and LIML_14180) and a thiol peroxidase (LIML_14175) exhibited also
a higher expression in the perRAperRB mutant (Log₂FC of 2.36, 1.93, and 2.04 respectively,
Fig 8B). All these up-regulated factors (except DoxX) were also up-regulated upon exposure
to deadly H₂O₂ dose [27] and they probably participate in the higher tolerance of the double
mutant in the presence of oxidants. Despite the up-regulation of several factors involved in
the defense against ROS, the DNA repair protein RadC (encoded by LIMLP_11400) and the
glutathione S transferase (encoded by LIMLP_13670) were notably down-regulated in the
*perRaperRB* mutant (Log2FC of -1.9 and -2.3, respectively) (Fig 8B and S4 Table).

Strikingly, several down-regulated ORFs in the double *perRaperRB* mutant such as *clpB*,
*ligA*, *ligB*, and the operon *lvrAB* have been associated with *Leptospira* virulence. As in many
bacteria, leptospiral ClpB ATPase is involved in disaggregating protein aggregates arising
upon stress-induced protein denaturation [41]. *ClpB* expression is increased upon exposure to
H$_2$O$_2$ and it is required for *Leptospira* virulence [27,42]. The ClpB-encoding ORF
(LIMLP_10060) is dramatically down-regulated in the *perRaperRB* mutant (Log2FC of -2.99)
(Fig 8D and S4 Table).

Another virulence factors in *Leptospira* are the immunoglobulin-like LigA (LIMLP_15405)
and LigB (LIMLP_15415) proteins. These surface-exposed proteins are involved in adhesion
to host cells through ECM binding [43] and participate in the immune evasion through
binding to the host complement Factor H and C4b binding protein [44]. Simultaneous down-
regulation of *ligA* and *ligB* expression led to attenuation of *Leptospira* virulence [45]. LigA
and *ligB* were down-regulated in the *perRaperRB* mutant (Log2FC of -3 and -2.44,
respectively) (Fig 8D and S5 Table).

*LvrA* (LIMLP_08490) and *lvrB* (LIMLP_08485) encode a hybrid histidine kinase and a
hybrid response regulator, respectively. Inactivation of the *lvrAB* operon led to virulence
attenuation in *L. interrogans* [46]. *LvrA* and *lvrB* had both a decreased expression in the
*perRaperRB* mutant (Log2FC of -2.3) (Fig 8D and S5 Table).

Additional ORFs encoding chaperones (the small heat shock proteins Hsp15 and Hsp20) or
enzymes involved in protein folding (the disulfide isomerase DsbD and the peptidyl-prolyl
cis-trans isomerase SlyD) and degradation (HtpX) were down-regulated in the *perRaperRB*
mutant. The involvement of these factors in *Leptospira* virulence has not been demonstrated
but small Hsps participate in *M. tuberculosis* growth in macrophages [47]. DsbD and these
two small Hsps were up-regulated in *L. interrogans* upon exposure to H$_2$O$_2$ [27]. All these factors might protect *Leptospira* proteostasis under adverse conditions as encountered during infection inside a host. The down-regulation of these virulence-associated genes together with the differential expression of several other genes was confirmed by RT-qPCR (S5 Fig). Interestingly, gene expression of the virulence-associated genes (*lvrA*, *lvrB*, *ligA*, *ligB*, *clpB*, *hsp15*, and *hsp20*) was increased to the WT level (or even to a higher level) in the double *perRAperRB* mutant strain complemented in trans only with *perRB* (Fig 9).

Taken together, these findings indicate that the loss of virulence resulting from the concomitant inactivation of *perRA* and *perRB* correlated with a global deregulation of a complex gene network, including genes associated with virulence.

**Identification of differentially-expressed non-coding RNAs in the *perRB* and *perRAperRB* mutants.**

Intergenic regions were also analyzed to identify differentially expressed predicted non-coding RNAs (ncRNAs). As observed for coding sequences, inactivation of *perRB* led to the deregulation of only a few putative ncRNAs and most of the changes in expression were below two folds (see S6 Table for a complete set of data). Nonetheless, a few numbers of ncRNAs were significantly down-regulated with a Log$_2$FC below -1 (S7 Table). Some of the differentially-expressed ncRNAs (*LepncRNA36*, *LepncRNA87*, *LepncRNA89*, *LepncRNA109*, *LepncRNA139*) were located in the proximate vicinity of differentially-expressed ORFs in the *perRB* mutant. Three ncRNAs (*LepncRNA35*, *LepncRNA89* and *LepncRNA109*) were also differentially expressed upon *perRA* inactivation (S7 Table) [27].

55 putative ncRNAs were differentially-expressed (with a Log$_2$FC cutoff of ±1) in the *perRAperRB* mutant and several of them were adjacent or overlapped differentially-expressed
ORFs (S8 Table). Only a few of these differentially-expressed ncRNAs had an altered expression in the single perRA and perRB mutant (S8 Table) [27]. Among the most highly differentially-expressed ncRNAs was LepncRNA38 that was located downstream ccp, a highly up-regulated ORF in the perRAperRB mutant (Fig 10 and S8 Table). LepncRNA38 and ccp were also up-regulated in the perRA mutant [27]. The ncRNA LepncRNA49, which was down-regulated in the perRAperRB mutant, overlapped with exbB (LIMLP_04255), an ORF that was also down-regulated in the double perRAperRB mutant as well as in the single perRA and perRB mutants (Fig 10). The down-regulated LepncRNA105 and LepncRNA130 ncRNAs were located downstream the hsp20-15 operon and gst, respectively, three ORFs whose expression is decreased is the perRAperRB mutant (Fig 10 and S8 Table). It is worth noting that LepncRNA38, LepncRNA105 and LepncRNA130 are up-regulated by H₂O₂ as were ccp, hsp20-15 and gst ([27]; Fig 10).

Altogether, these findings indicate that the absence of both PerRA and perRB triggers major changes in the transcriptional activity of many ncRNAs in L. interrogans, that could consequently alter the expression of many ORFs.
Discussion

Virulence mechanisms are poorly characterized in pathogenic *Leptospira*. These bacteria possess a high number of genes encoding proteins of unknown function (40% of the genomes) and many of them are pathogen-specific. Pathogenic *Leptospira* spp. lack many classical virulence factors, such as a type III to type VI secretion systems, and it is unclear which factors are important for its pathogenesis. It is therefore generally agreed that these pathogens possess unique virulence factors. Nonetheless, studying heme oxygenase and catalase mutants have shown that, *in vivo*, iron acquisition and defense against peroxide stress are important virulence-associated mechanisms in *L. interrogans* [11,48]. Catalase is repressed by PerRA [24,27] and genes encoding factors involved in iron uptake are very likely controlled by regulators of the Fur-family.

In addition to PerRA, pathogenic *Leptospira* contain three other ORFs annotated as Furs. In the present study, we have characterized the *L. interrogans* Fur-like regulator encoded by LIMLP_05620 and showed that it exhibits characteristic features of a PerR regulator. We consequently named this ORF *perRB*. Sequence alignment and phylogenetic analyses revealed that PerRB is the closest relative to the already characterized PerRA, and perhaps more importantly, they both do exhibit the canonical amino acid residues that are the hallmark of a PerR. The H$_2$O$_2$ sensing histidine and aspartate residues are conserved in *Leptospira* PerRA and PerRB and, interestingly, both genes are H$_2$O$_2$-responsive, albeit with different apparent sensitivity. This is consistent with a mechanism whereby PerRA and PerRB would repress their own transcription and dissociate from their promoter upon oxidation by H$_2$O$_2$, leading to alleviation of repression. Moreover, the higher survival of the *perRB* mutant in the presence of superoxide suggests a derepression of genes encoding defenses against ROS and therefore the participation of PerRB in controlling the adaptation to oxidative stress. Neither
perRA nor perRB expression was up-regulated in iron-limiting condition [24]. Although the putative lipoprotein LIMLP_18755 was significantly up-regulated in the perRB mutant and under iron-limiting condition, there was no strong overlap between PerRB regulon and the transcriptional response to iron-limiting condition [24]. Altogether, these findings could argue in favor of LIMLP_05620 encoding a PerR-like regulator rather than a Fur. However, because iron homeostasis and oxidative stress are intertwined, a certain functional relationship has been observed between PerR and Fur. In several bacteria where PerR and Fur coexist, including *B. subtilis* and *C. jejuni*, the PerR regulon overlaps with that of Fur [49,50]. In addition, *fur* and several Fur-regulated genes are also differentially expressed in the presence of H$_2$O$_2$ [51,52]. In fact, PerR represses *fur*, whose expression is up-regulated in the presence of H$_2$O$_2$ as a consequence of dissociation of PerR from the *fur* promoter [53,54]. Metal-catalyzed oxidation of the H$_2$O$_2$ sensing residues will be fundamental in establishing that the Per-like regulator encoded by LIMLP_05620 is a *bona fide* PerR.

To the best of our knowledge, this is the first report that has identified the coexistence of two PerR regulators in a pathogenic Gram-negative bacterium. The coexistence of three PerR-like regulators has been reported only in Gram-positive bacteria such as *B. licheniformis* and *M. smegmatis*. It was shown that the three *B. licheniformis* PerRs sense hydrogen peroxide by histidine oxidation, although with different sensitivity [55]. In *M. smegmatis*, three Fur-like paralogs displayed the canonical PerR Asp residue involved in H$_2$O$_2$ sensitivity, exhibited H$_2$O$_2$ sensing by metal-catalyzed histidine oxidation and a higher H$_2$O$_2$ resistance when their genes were inactivated [56].

One important question was to understand the mechanism that have led to the coexistence of PerRA and PerRB exclusively in highly virulent species (P1 clade). Virulent mammalian-adapted strains in the *Leptospira* genus might have originated from a free-living ancestor inhabiting soils. The phylogenetic analysis presented here indicates that the coexistence of
PerRA and PerRB is not due to gene duplication. Indeed, PerRA was already present in the leptospirales ancestor whereas PerRB was probably acquired by pathogenic species by horizontal transfer from a soil/aquatic bacterium of another phylum. In this scenario, PerRA would had been lost by the P2 clade intermediate species but maintained together with PerRB by the P1 clade species to establish full virulence.

We had previously shown that when \textit{perRA} was inactivated, \textit{L. interrogans} acquired a higher resistance to H$_2$O$_2$ explained by the derepression of \textit{katE}, \textit{ahpC} and \textit{ccp} [24,27]. Here, we have demonstrated that inactivating \textit{perRB} resulted in a higher survival of \textit{L. interrogans} in the presence of the superoxide but it did not affect the survival of \textit{L. interrogans} in the presence of H$_2$O$_2$. Therefore, even though \textit{perRB} is up-regulated upon exposure to H$_2$O$_2$ as \textit{perRA}, the consequence of \textit{perRB} inactivation is different than that of \textit{perRA}, suggesting that PerRA and PerRB have a distinct and non-redundant function in \textit{Leptospira} adaptation to oxidative stress. The distinct repartition of PerRA and PerRB in the \textit{Leptospira} genus and differences in their respective regulon support the hypothesis of a non-redundant function in the adaptation to oxidative stress. The PerRA and PerRB regulons determined when \textit{L. interrogans} are cultivated inside a host using DMC implemented in rats confirmed the limited overlap between PerRA and PerRB regulons [57].

Phenotypic studies suggest that PerRB represses (directly or indirectly) genes encoding defenses against superoxide. Highly pathogenic \textit{Leptospira} species (from the P1 clade) do not encode any SOD or SOR that could be responsible for detoxification of superoxide whereas intermediated species (P2 clade) and saprophyte non-pathogenic \textit{Leptospira} do have such enzymes. Understanding how pathogenic \textit{Leptospira} detoxify superoxide encountered during infection is a very important question. Overall, the differentially-expressed genes upon \textit{perRB} inactivation are mostly \textit{Leptospira}-specific and poorly characterized. Examining the PerRB regulon determined when \textit{Leptospira} are cultivated in laboratory conditions did not allow to
draw a conclusive hypothesis on the identity of the factors that could participate in superoxide
detoxification in *L. interrogans*. The highest differentially-expressed ORFs were mainly
involved in regulation and cell signaling (transcription and sigma factors,
adenylate/diguanylate cyclase, TCSs) and could be involved in regulating the adaptation to
various challenging stress encountered in the environment or within a host. Further studies
will be required to determine whether superoxide detoxification in *L. interrogans* is mediated
by enzymatic detoxification or metal-dependent scavenging mechanisms and to clarify the
exact role of PerRB in controlling those pathways.

The low number of significantly differentially-expressed genes in the *perRB* mutant when *L.
interrogans* are cultivated *in vitro* led us to propose that PerRB exerts its function during
oxidative stress or upon host-related conditions. Consistent with this hypothesis is the up-
regulation of *perRB* in the presence of lethal H$_2$O$_2$ dose. It is worth noting that there is, to
some extent, an overlap between the PerRB regulon and the differentially-expressed genes
upon exposure to lethal H$_2$O$_2$ dose [27]. Moreover, the exclusive presence of PerRB in the
pathogenic *Leptospira* clades strongly suggests that PerRB function is more related to
regulating adaptation to infection-related conditions rather than to environmental survival.

Very interestingly, when the *perRB* mutant was cultivated in the host conditions using the
DMC implants, a higher number of genes were differentially-expressed with greater fold
changes than when the *perRB* mutant was cultivated at 30°C in the laboratory conditions [57].

Notably, in the host condition, the absence of *perRB* also led to the deregulation of several
genes involved in signaling and regulation, which is consistent with a role of PerRB in
regulating adaptation to the host environment [57].

One feature of *Leptospira* genus is the genetic and functional redundancy where multiple
genes commonly encode for a similar function. The development of genetic tools has made
random and targeted mutagenesis possible, albeit with a low efficiency. Due to this limitation,
only a few *Leptospira* virulence factors have been identified and have fulfilled Koch's molecular postulates. The present study is the first to report the concomitant inactivation of two genes and complementation of a double mutant in a pathogenic *Leptospira*. Obtaining a double *perRAperRB* mutant gave us the unique opportunity to investigate the functional relationship between two PerR-like regulators in a pathogenic bacterium.

In many pathogens which contain only one PerR paralog, such as *N. gonorrhoeae*, *S. pyogenes*, and *S. aureus*, PerR was shown to be involved in virulence [54,58–61]. The single *L. interrogans* *perRA* and *perRB* mutants still retain full virulence in the model for acute leptospirosis (this study and [24]). Interestingly, virulence attenuation was only observed upon the concomitant inactivation of *perRA* and *perRB*, suggesting an interplay in controlling (directly or indirectly) *L. interrogans* virulence-associated genes. The loss of virulence correlated with a large differential gene and ncRNA expression compared not only with the WT but also with the single mutant strains. In other words, the double *perRAperRB* displayed differential gene expression that were not observed in the single *perRA* and *perRB* mutants. This could indicate that a subset of genes and ncRNAs is controlled by both PerRA and PerRB. The absence of one regulator could be compensated by the other and most of the genes and ncRNAs that can be regulated by the two regulators would not be differentially expressed in the single mutants. The few genes (LIMLP_02010, LIMLP_04255, LIMLP_04235, LIMLP_11810, LIMLP_14225, LILP_15470, and LIMLP_18235) and ncRNAs that display differential expression in the single mutants in our transcriptomic studies (this study and [27]) indicate a certain functional redundancy of the two regulators even if the phenotypic analyses of the mutants suggest distinct functions. The change in expression of a few regulators when PerRA and PerRB are both absent could lead to major changes in expression of many ORFs or ncRNAs in cascade. One can also speculate that among the large differentially-expressed genes only observed in the double *perRAperRB*
mutant some deregulation might be due to a compensatory effect to maintain a productive
fitness.

Despite a higher ability to resist ROS, the double perRAperRB mutant has lost its virulence; it
could not trigger acute leptospirosis-associated morbidity. This could be obviously explained
by a significant lower expression of several virulence-associated factors in the double
perRAperRB mutant, such as LigA, LigB, LvrA, LvrB, and ClpB. In addition, other
dramatically down-regulated genes encode factors such as small Hsps (Hsp15 and Hsp20) for
which a role in bacterial virulence is demonstrated in other bacteria including M. tuberculosis
[62]. Moreover, several differentially-expressed ORFs of unknown function could also be
responsible for the loss of virulence of the double perRAperRB mutant. It is noteworthy that
the double perRAperRB mutant was also unable to colonize mice [57] and, consistent with
what is observed with in vitro-cultivated perRAperRB mutant, this correlated with dramatic
gene dysregulation including down-regulation of ligA and ligB [57].

In summary, this study has allowed to identify a second PerR-like regulator in pathogenic L.
interrogans strains that cooperates with PerRA to control the adaptation to oxidative stress
and virulence. By concomitantly inactivating perRA and perRB and establishing the molecular
Koch’ postulates, we have unveiled a complex regulatory network that reveals, for the first
time, a functional relationship between PerR regulators and Leptospira virulence, most likely
through the regulation of virulence- and pathogenicity-associated factors.
Materials and Methods

Bacterial strains and growth condition

*L. interrogans* serovar Manilae strain L495, *perRA* (M776), *perRB* (M1474), and the double *perRAperRB* mutant strains (see S9 Table for a complete description of the strains used in this study) were grown aerobically at 30°C in Ellinghausen-McCullough-Johnson-Harris medium (EMJH) [63] with shaking at 100 rpm. *Leptospira* growth was followed by measuring the absorbance at 420 nm. *β2163 and Π1 E. coli* strains were cultivated at 37°C in Luria-Bertani medium with shaking at 37°C in the presence of 0.3 mM thymidine or diaminopimelic acid (Sigma-Aldrich), respectively. When needed, spectinomycin, kanamycin and gentamycin were added at the respective concentration of 50 µg/ml, 30 µg/ml, and 8 µg/ml.

Concomitant inactivation of *perRA* (LIMLP_10155) and *perRB* (LIMLP_05620).

*PerRA* gene (LIMLP_10155/LIC12034/LA1857) was inactivated in the *perRB* (LIMLP_05620/LIC11158/LA2887) mutant strain (M1474, *perRB::Km*6) by introduction of a spectinomycin resistance cassette (S4 Fig). For this, a spectinomycin resistance cassette flanked by 0.8 kb sequences homologous to the sequences flanking *perRA* was created by gene synthesis (GeneArt, Life Technologies) and cloned into a kanamycin-resistant *Escherichia coli* vector unable to replicate in *Leptospira*. The obtained suicide plasmid (pKΔperRA) (S10 Table) was introduced in the *perRB* mutant strain by electroporation as previously described [64] using a Gene Pulser Xcell (Biorad). Individual spectinomycin-resistant colonies were selected on EMJH plates containing 50 µg/ml spectinomycin and screened by PCR (using the P1 and P2 primer set, see S11 Table) for proper replacement of the *perRA* coding sequence by the spectinomycin resistance cassette. *PerRA* inactivation in the double *perRAperRB* mutant was verified by western blot using an anti-PerRA serum (S4 Fig).
Complementation of the single *perRB* and double *perRAperRB* mutants

The *perRB* mutant (*perRB::Km*<sup>R</sup>) complementation was performed by expressing the *perRB* ORF in the pMaORI replicative vector [65]. The *perRB* (LIMLP_05620) ORF together with its native promoter region (200 bp upstream region) were amplified from genomic DNA of *L. interrogans* serovar Manilae strain L495 (using the ComPerR2_5Not and ComPerR2_3Xba primer set, S11 Table) and cloned between the NotI and XbaI restriction sites in the pMaORI vector. The absence of mutation in the *perRB* ORF in the obtained plasmid (pNB139) was checked by DNA sequencing and the pNB139 plasmid was introduced in the *perRB* mutant (M1474) by conjugation using the *E. coli* β2163 conjugating strain as previously described [66]. *Leptospira* conjugants were selected on EMJH plates containing 50 µg/ml spectinomycin and resistant colonies were then inoculated into liquid EMJH medium supplemented with spectinomycin for further analysis. The restoration of *PerRB* expression in the complemented *perRB* mutant was verified by RT-qPCR.

The double *perRAperRB* mutant (*ΔperRA, perRB::Km*<sup>R</sup>) complementation required the construction of a gentamycin resistant pMaORI complementation vector. A gentamycin resistant cassette [67] was cloned into the pMaORI between the NotI and XbaI restriction sites and the integrity of the gentamycin resistance cassette in the pMaORIgenta plasmid (S10 Table) was checked by DNA sequencing. Then, the *perRB* ORF (LIMLP_05620) together with its native promoter region (248 bp upstream region) were amplified (using the F-ApaI-PerR2genta and R-ApaI-PerR2genta primer set, S11 Table) from genomic DNA of *L. interrogans* serovar Manilae strain L495 and cloned into the PCR-blunt II TOPO vector (Zero Blunt TOPO PCR cloning kit, Invitrogen). The *perRB* locus was subsequently subcloned into the pMaORIgenta plasmid at the ApaI restriction site. The obtained plasmid (pCZ3, S10 Table) or the empty pMaORIgenta plasmids were introduced in *perRAperRB* double...
Leptospira mutant strain by conjugation using the E. coli β2163 conjugating strain as previously described [66]. Leptospira conjugants were selected on EMJH plates containing 8 µg/ml gentamycin and resistant colonies were then inoculated into liquid EMJH medium supplemented with gentamycin and spectinomycin for further analysis. The restoration of PerRB expression in the trans-complemented double perRAperRB mutant was verified by RT-qPCR (S4 Fig).

Phylogenetic analyses

The sequences homologous to the LIMLP_10155 (PerRA), LIMLP_05620 (PerRB), LIMLP_18590 and LIMLP_04825 proteins were searched with BLASTP version 2.10.0 among the other Leptospira species (Fig 3 and S1 Table) or among the protein sequences of 11,070 representative genomes (Fig 2), as previously described [68]. In that case, only the sequences with an e-value less than 1e-10 and a percentage of similarity greater than 60% were retained. Sequences with percent identity equal to 100% were clustered by CD-HIT version 4.8.1 and only one sequence was retained. The resulting 1671 sequences were subsequently aligned by MAFFT version 7.471. A phylogenetic tree was finally built with IQ-TREE version 2.1.1 under the best-fit model LG + R10. A second phylogenetic tree was made with a subset of sequences to improve the resolution of the separation between PerRA and PerRB. The same procedure was followed, except that the best-fit model used for phylogenetic reconstruction is LG + R5. Both trees were visualized with FigTree version 1.4.4 (https://github.com/rambaut/figtree).

RNA purification

Virulent L. interrogans serovar Manilae strain L495 and perRB (M1474) mutant strains with less than three in vitro passages were used in this study. Four independent biological
replicates of exponentially grown *L. interrogans* WT, *perRB* (M1474) and double
*perRAperRB* mutant strains were harvested and resuspended in 1 ml TRIzol (ThermoFisher
Scientific) and stored at -80°C. Nucleic Acids were extracted with chloroform and
precipitated with isopropanol as described earlier [69]. Contaminating genomic DNA was
removed by DNase treatment using the RNase-free Turbo DNA-free turbo kit
(ThermoFisher Scientific) as described by the manufacturer. The integrity of RNAs (RIN >
8.0) was verified by the Agilent Bioanalyzer RNA NanoChips (Agilent technologies,
Wilmington, DE).

**RNA Sequencing**

rRNA were depleted from 0.5 µg of total RNA using the Ribo-Zero rRNA Removal Kit
(Bacteria) from Illumina. Sequencing libraries were constructed using the TruSeq Stranded
mRNA Sample preparation kit (20020595) following the manufacturer’s instructions
(Illumina). The directional libraries were controlled on Bioanalyzer DNA1000 Chips (Agilent
Technologies) and concentrations measured with the Qubit dsDNA HS Assay Kit
(ThermoFisher). Sequences of 65 bases were generated on the Illumina Hiseq 2500
sequencer.

Bioinformatics analyses were performed using the RNA-seq pipeline from Sequana [70].
Reads were cleaned of adapter sequences and low-quality sequences using cutadapt version
1.11 [71]. Only sequences at least 25 nt in length were considered for further analysis. Bowtie
version 1.2.2 [72], with default parameters, was used for alignment on the reference genome
(*L. interrogans* serovar Manilae strain UP-MMC-NIID LP, from MicroScope Platform).

Genes were counted using featureCounts version 1.4.6-p3 [73] from Subreads package
(parameters: -t gene -g locus_tag -s 1).
Count data were analyzed using R version 3.5.1 [74] and the Bioconductor package DESeq2 version 1.20.0 [75]. The normalization and dispersion estimation were performed with DESeq2 using the default parameters and statistical tests for differential expression were performed applying the independent filtering algorithm. Differential expressions were expressed as logarithm to base 2 of fold change (Log$_2$FC). A generalized linear model including the replicate effect as blocking factor was set in order to test for the differential expression between *Leptospira* samples. Raw p-values were adjusted for multiple testing according to the Benjamini and Hochberg (BH) procedure [76] and genes with an adjusted p-value lower than 0.05 and a Log$_2$FC higher than 1 or lower than -1 were considered differentially expressed. Heat maps and Volcano plots were generated using the Galaxy platform (https://usegalaxy.eu/).

**Quantitative RT-PCR experiments**

cDNA synthesis was performed with the cDNA synthesis kit (Biorad) according to the manufacturer’s recommendation. Quantitative PCR was conducted in triplicate with the SsoFast EvaGreen Supermix (Biorad) as previously described. LIMLP_06735 was used as a reference gene.

**Non-coding RNA identification**

Sequencing data from the *L. interrogans* WT, *perRB* (M1474) and double *perRaperRB* mutant strains were processed with Trimmomatic [77] to remove low-quality bases and adapter contaminations. BWA mem (version 0.7.12) was used to discard the reads matching *Leptospira* rRNA, tRNA or polyA sequences and to assign the resulting reads to *Leptospira* replicons. Then Rockhopper [78] was used to re-align reads corresponding to separate replicons and to assemble transcripts models. The output was filtered to retain all transcripts.
longer than 50 nucleotides not overlapping within 10 nucleotides with NCBI annotated genes on the same orientation, and showing a minimum Rockhopper raw count value of 50 in at least two isolates. This high-quality set of new sRNA was subjected to differential expression analysis with Rockhopper, adopting a Benjamini-Hochberg adjusted P-value threshold of 0.01. For each non-coding RNAs, putative function was identified by BLAST using the Rfam database [79].

**Infection experiments**

WT and mutant *L. interrogans* strains were cultivated in EMJH medium until the exponential phase and counted under a dark-field microscope using a Petroff-Hauser cell. $10^4$ or $10^6$ bacteria (in 0.5 ml) were injected intraperitoneally in groups of 4-8 male 4 weeks-old Syrian Golden hamsters (RjHan:AURA, Janvier Labs). Animals were monitored daily and sacrificed by carbon dioxide inhalation when endpoint criteria were met (sign of distress, morbidity).

**Ethics Statement**

The protocol for animal experimentation was reviewed by the Institut Pasteur (Paris, France), the competent authority, for compliance with the French and European regulations on Animal Welfare and with Public Health Service recommendations. This project has been reviewed and approved (CETEA #2016-0019) by the Institut Pasteur ethic committee for animal experimentation, agreed by the French Ministry of Agriculture.

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Supporting information

S1 Fig. Phylogenetic analysis of the four Fur-like regulators of *L. interrogans*.

Extended phylogenetic tree showing the separation between PerRA (red) and PerRB (blue).

S2 Fig. Growth of the *L. interrogans* perRA and perRB mutants in the presence of H₂O₂.

*L. interrogans* WT (black circles), perRA (cyan up-pointing triangles) and perRB (green down-pointing triangles) mutant strains were cultivated in EMJH medium at 30°C in the absence (A) or presence of 2 mM H₂O₂ (B). *Leptospira* growth was assessed by absorbance at 420 nm. Data are means and standard errors of three independent biological experiments.

S3 Fig. Analysis of the *L. interrogans* PerRB regulon.

(A) Venn diagram showing the overlap of differentially-expressed ORFs (with an adjusted p-value < 0.05) in the perRA and perRB mutants. Differentially-expressed genes in the perRB mutant (as determined in this study) (in green) were compared with those in the perRA mutant as determined previously [27] (in cyan). The down- and up-regulated ORFs in both mutants were indicated in blue and red, respectively. (B) Comparison of differentially-expressed ORFs (with an adjusted p-value < 0.05) in the perRB mutant and upon *L. interrogans* exposure to H₂O₂. Log₂FC of differentially-expressed ORFs upon *L. interrogans* exposure to 1 mM H₂O₂ (as determined previously [27] was plotted against the Log₂FC of differentially-expressed ORFs upon *perRB* inactivation. Down- and up-regulated ORFs in the perRB mutant were represented by blue and red symbols, respectively, and the name of selected ORFs was indicated. The dashed lines indicate a Log₂FC value of zero. Please note that only differentially-expressed ORFs in both conditions were considered.
S4 Fig. Characterization and complementation of the double perRAperRB mutant strain.

(A) Schematic representation of the double perRAperRB mutant construction. PerRA (LIMLP_10155) was inactivated by allelic exchange in the transposon perRB mutant. The kanamycin (Km) and spectinomycin (Spc) resistance cassettes inactivating perRB and perRA, respectively, are indicated. (B) Production of PerRA in the WT, in the single perRA and perRB mutants and in the double perRAperRB mutant strains. L. interrogans strains were cultivated in EMJH medium at 30°C until the logarithmic phase and lysed by sonication. 10 μg of total lyzates were resolved on a 15% SDS-PAGE and transferred on nitrocellulose membrane. PerRA was detected by immunoblot using a 1/2000 antibody dilution as described previously [30]. (C) PerRB expression in the WT, in the double perRAperRB mutant and in the trans-complemented perRAperRB mutant with the perRB ORF. RNAs were extracted from exponentially-grown L. interrogans strains and perRB expression was assessed by RT-qPCR in triplicate using flaB gene (LIMLP_09410) as reference gene. PerRB expression in the perRAperRB and trans-complemented mutant strains were normalized against that in the WT strain. (D) Growth of stationary phase-adapted WT, perRAperRB and trans-complemented perRAperRB mutant strains. L. interrogans WT (black circles), perRAperRB mutant (pink squares) and perRAperRB mutant trans-complemented with the perRB ORF (blue triangles) were cultivated in EMJH medium at 30°C until late stationary phase (7 days after the entry in the stationary phase) and used to inoculate EMJH medium. Bacteria were then cultivated at 30°C and growth was assessed by absorbance at 420 nm. Data are means and standard errors of three independent biological experiments.

S5 Fig. RT-qPCR experiments in the double perRAperRB mutant.

RNAs were extracted from exponentially-grown L. interrogans strains WT or double
perRAperRB mutant (m). Expression of the indicated genes was measured by RT-qPCR using the LIMLP_06735 as reference gene. Gene expression in the perRAperRB mutant was normalized against that in the WT strain. Fold change values are indicated in blue. Statistical significance was determined by a Two-way Anova test in comparison with the WT samples. ****, p-value<0.0001; **, p-value<0.005.

S1 Table. Distribution of the four Fur-like regulators of Leptospira interrogans in the genus Leptospira.

S2 Table. Complete set of ORF expression in Leptospira interrogans WT and M1474 perRB mutant.

S3 Table. Complete set of ORF expression in Leptospira interrogans WT and double perRAperRB mutant.

S4 Table. Selected down-regulated genes in the perRAperRB double mutant.

S5 Table. Selected up-regulated genes in the perRAperRB double mutant.

S6 Table. Complete set of differentially-expressed predicted non coding RNAs in the perRB (M1474) and in the double perRAperRB mutant strains of Leptospira interrogans.

S7 Table. Selected differentially-expressed non-coding RNAs in the perRB mutant

S8 Table. Selected differentially-expressed non-coding RNAs in the perRAperRB mutant.
S9 Table. Strains used in this study

S10 Table. Plasmids used in this study

S11 Table. Primers used in this study
Figure legends

Fig 1. Analysis of the four Fur-like regulators of *L. interrogans*.

(A) Schematic representation of the domain organization of a typical Fur-like regulator. The N-terminal DNA binding domain and the C-terminal dimerization domain are represented in grey and golden, respectively. The α-helix and β-strand secondary structures are indicated below in green and blue, respectively. The His, Asp and Glu residues involved in regulatory metal coordination are designated in green. The Arg/Asn residue involved in DNA binding specificity is marked in red. The Arg/Asn (involved in DNA binding specificity) and Asp/Glu residues (involved in H$_2$O$_2$ sensitivity) that allow distinguishing a Fur from a PerR are further emphasized with a grey arrow head. The two cysteinate motifs in the C-terminal domain involved in structural metal coordination are represented by the double blue lines in the C-terminal dimerization domain. (B) Comparison of the four Fur-like regulators of *L. interrogans* (LIMLP_10155, LIMLP_05620, LIMLP_04825, LIMLP_18590) with *B. subtilis* Fur and PerR. Primary sequence alignment was obtained by Clustal Omega ([https://www.ebi.ac.uk/Tools/msa/clustalo/](https://www.ebi.ac.uk/Tools/msa/clustalo/); [80]). The H4 DNA binding helix is underlined and the Arg/Asn residue involved in DNA binding specificity is designated in red. The residues of the regulatory metal coordination, including the Asp/Glu residue involved in H$_2$O$_2$ sensitivity, are marked in green and indicated with an asterisk. The Arg/Asn and Asp/Glu residues that allow distinguishing a Fur from a PerR are further emphasized with a grey arrow head. The cysteine residues of the structural metal coordination are marked in cyan. (C) Cartoon representation of the crystal structure of LIMLP_10155 (5NL9) and of the modeled structure of LIMLP_05620, LIMLP_04825 and LIMLP_18590. The modeled structures were obtained by searching homologies between LIMLP_05620, LIMLP_04825 and
LIMLP_18590 and protein with known crystal structure using PHYRE2 ([http://www.sbg.bio.ic.ac.uk/~phyre2/html/page.cgi?id=index; [81]). Secondary structures are numbered as in (A).

**Fig 2.** (A) Phylogenetic tree with a cartoon representation showing the distribution of the 1671 sequences putatively homologous to the LIMLP_10155 (PerRA, cyan triangle), LIMLP_05620 (PerRB, green triangle), LIMLP_18590 (yellow triangle) and LIMLP_04825 (red triangle) proteins. The gray triangles represent groups which are not monophyletic with the *Leptospira* sequences and which may therefore originate from other types of PerR or have had a species-specific evolution. (B) Phylogenetic tree showing the separation between PerRA (cyan) and PerRB (green).

**Fig 3. Distribution of the four Fur-like regulators of *L. interrogans* in the genus *Leptospira.*
Circular phylogenetic tree with inner circles indicating the homology between each Fur-like regulator of *L. interrogans* with the closest homolog among representative genomes of *Leptospira* species. The branches are colored according to their classification into the four main subclades with P1 (highly pathogenic) in red, P2 (intermediates) in magenta, S1 (saprophytes) in yellow and S2 (new clade saprophytes) in blue [68]. The inner circles are, from the inside to the outside, LIMLP_10155, LIMLP_05620, LIMLP_04825 and LIMLP_18590. The green color gradient indicates the degree of homology (See S1 Table), grey and black indicate the presence of a false positive and the absence of orthologs, respectively.

**Fig 4.** Increased *PerRA* and *perRB* expression upon exposure to hydrogen peroxide.
Exponentially growing *L. interrogans* were incubated in the absence or presence of 10 μM (for 30 min.) or 1 mM H₂O₂ (for 60 min.) and *perRA* (cyan circles) and *perRB* (green squares) expression was measured by RT-qPCR as described in Material and Methods section. Gene expression was normalized by that in untreated samples. Data are the means and standard errors of three independent biological replicates. P-values obtained by a Two-way Anova test indicates the statistical significance in comparison with untreated samples.

**Fig 5. Effect of *perRB* inactivation on *Leptospira* growth in the presence of superoxide-generating paraquat.**

*L. interrogans* WT containing the empty pMaORI vector (black circles), the *perRB* mutant containing the empty pMaORI vector (green triangles) or the *perRB* mutant containing the pMaORI vector expressing LIMLP_05620 (red squares) were cultivated in EMJH medium in the absence (A) or in the presence of 2 μM Paraquat (B). Growth was assessed by measure of absorbance at 420 nm. Data are means and standard errors of three independent biological replicates.

**Fig 6. Effect of concomitant inactivation of *perRA* and *perRB* on *Leptospira* growth in the presence of ROS and virulence.**

*L. interrogans* WT (black circles), the single *perRA* mutant (cyan up-pointing triangles), the single *perRB* mutants (green down-pointing triangles) or the double *perRAperRB* mutant (pink squares) were cultivated in EMJH medium in the absence (A), or in the presence of 2 mM H₂O₂ (B) or of 2 μM paraquat (C). Complementation of the double *perRAperRB* mutant with *perRB* ORF (presented in (D)) was performed by cultivating *L. interrogans* WT containing the empty pMaORIgenta vector (black circles), the double *perRAperRB* mutant containing the empty pMaORIgenta vector (pink squares) or the double *perRAperRB* mutant...
containing the pMaORIgenta vector expressing LIMLP_05620 (blue triangles) in the presence of 2 µM paraquat. Growth was assessed by measure of absorbance at 420 nm and the data are means and standard errors of three independent biological replicates. (E) Virulence was assessed by infecting hamsters (n=4) by peritoneal route with $10^4$ of WT (black circles), single perRA or perRB mutants (cyan and green triangles, respectively), or the double perRAperRB mutant (pink squares) as described in Material and Methods section. (F) Complementation of the double perRAperRB mutant with perRB was performed by infecting hamsters (n=8) by peritoneal route with $10^6$ of WT containing the empty pMaORIgenta vector (black circles), of the double perRAperRB mutant containing the empty pMaORIgenta vector (pink squares) or the double perRAperRB mutant containing the pMaORIgenta vector expressing LIMLP_05620 (blue triangles).

Fig 7. Differential gene expression in the perRAperRB mutant.
(A) Venn diagram showing the overlap of differentially-expressed ORFs (with an adjusted p-value < 0.05) in the double perRAperRB mutant (in pink) with those of the perRA mutant (as determined by Zavala-Alvarado et al. [27]) (in cyan) and of the perRB mutant (as determined in this study) (in green). (B)-(D) Volcano scatter representation of differentially-expressed genes in the perRAperRB mutant (B), in the single perRA mutant (as determined by Zavala-Alvarado et al. [27]) (C), and in the single perRB mutant (as determined in this study) (D). Red and blue dots indicate significantly up- and down-regulated genes, respectively, with a $\log_2$FC cutoff of ±1 (dashed vertical lines) and p-value<0.05. Selected genes are labelled.

Fig 8. Comparison of differential gene expression in the double perRAperRB mutant with that in the single perRA and perRB mutants.
Expression of selected genes of the TonB-dependent transport cluster (A), involved in
oxidative stress and redox homeostasis (B), in regulation and signaling (C), and in virulence (D) determined by RNASeq in the double perRAperRB mutant was compared to that in the single perRA mutant determined by Zavala-Alvarado et al. [27] and single perRB mutant (as determined in this study). Differential expression in each mutant strain was normalized with that in the WT strain. Gene names are indicated on the right. The Heat Map color from blue to red indicates low to high Log₂FC.

Fig 9. Complementation of the perRAperRB mutant with perRB restores expression of virulence associated genes.

The WT containing the empty pMaORIgenta vector (black circles), the perRAperRB mutant containing the empty pMaORIgenta vector (pink circles) and the complemented perRAperRB mutant (blue circles) strains were cultivated in EMJH medium until the exponential phase. Cells were harvested and RNAs were purified, and the expression of lvrA, lvrB, ligA, ligB, clpB, hsp20 and hsp15 was measured by RT-qPCR. Gene expression was normalized by that in the WT strains. Data are the means and standard errors of three independent biological replicates. P-values obtained by a Two-way Anova test indicates the statistical significance in comparison with WT samples.

Fig 10. Non-coding RNAs expression in the double perRAperRB mutant.

Differential expression of selected ncRNAs (LepncRNA38, 49, 105, and 130) in the perRAperRB mutant (determined in this study) (a) was compared to those in the single perRA mutant, as determined by Zavala-Alvarado et al. [27] (b), in the single perRB mutant (determined by this study) (c), and upon exposure to 1 mM H₂O₂ for 1h00 as determined by Zavala-Alvarado et al. [27] (d). The location of the ncRNAs LepncRNA38, 49, 105, and 130 were represented schematically with the adjacent or overlapping ORFs. The values indicate...
the \( \log_2 \) FC of ncRNAs expression normalized with that in WT and the respective expression of these ORF (\( \log_2 \) FC) are indicated into parenthesis with the color corresponding to that of the ORF in the cartoon. NSC, non-significantly changed.
Fig 1
Fig 4
Fig 5
**A** TonB-dependent transport system

- LIMLP_04240 (tonB)
- LIMLP_02250 (exbD2)
- LIMLP_04250 (exbD1)
- LIMLP_04255 (exbB)
- LIMLP_04260 (Hypothetical)
- LIMLP_04265 (Hypothetical)
- LIMLP_04270 (tonB-dependent receptor/fecA)
- LIMLP_04275
- LIMLP_04280 (lipL48)

**B** Oxidative stress and redox-related

- LIMLP_02225 (doxX)
- LIMLP_02795 (ccp)
- LIMLP_05955 (ahpC)
- LIMLP_10145 (katE)
- LIMLP_10150 (ank)
- LIMLP_11400 (radC)
- LIMLP_13670 (yfcG/gst)
- LIMLP_14170 (Imelysin/truB)
- LIMLP_14175 (Thiol oxidoreductase)
- LIMLP_14180 (Imelysin)
- LIMLP_14715 (dps)

**C** Regulation and signaling

- LIMLP_00130 (A/G cyclase)
- LIMLP_02085 (A/G cyclase/cyaA15)
- LIMLP_04775 (PDE/rtn)
- LIMLP_05450 (DGC)
- LIMLP_05455 (DGC)
- LIMLP_05460 (DGC)
- LIMLP_05485 (DGC)
- LIMLP_05845 (DGC)
- LIMLP_07050 (DGC)
- LIMLP_09580 (PDE)
- LIMLP_18375 (PDE)

**D** Virulence-associated

- LIMLP_08485 (lvrB)
- LIMLP_08490 (lvrA)
- LIMLP_10060 (clpB)
- LIMLP_15405 (ligA)
- LIMLP_15415 (ligB)

Fig 8
Fig 10