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Comparative and functional genomics of *Legionella* identified eukaryotic like proteins as key players in host–pathogen interactions

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Although best known for its ability to cause severe pneumonia in people whose immune defenses are weakened, *Legionella pneumophila* and *Legionella longbeachae* are two species of a large genus of bacteria that are ubiquitous in nature, where they parasitize protozoa. Adaptation to the host environment and exploitation of host cell functions are critical for the success of these intracellular pathogens. The establishment and publication of the complete genome sequences of *L. pneumophila* and *L. longbeachae* isolates paved the way for major breakthroughs in understanding the biology of these organisms. In this review we present the knowledge gained from the analyses and comparison of the complete genome sequences of different *L. pneumophila* and *L. longbeachae* strains. Emphasis is given on putative virulence and *Legionella* life cycle related functions, such as the identification of an extended array of eukaryotic like proteins, many of which have been shown to modulate host cell functions to the pathogen's advantage. Surprisingly, many of the eukaryotic domain proteins identified in *L. pneumophila* as well as many substrates of the Dot/Icm type IV secretion system essential for intracellular replication are different between these two species, although they cause the same disease. Finally, evolutionary aspects regarding the eukaryotic like proteins in *Legionella* are discussed.

Keywords: *Legionella pneumophila*, *Legionella longbeachae*, evolution, comparative genomics, eukaryotic like proteins, virulence

INTRODUCTION

Genomics has the potential to provide an in depth understanding of the genetics, biochemistry, physiology, and pathogenesis of a microorganism. Furthermore comparative genomics, functional genomics, and related technologies, are helping to unravel the molecular basis of the pathogenesis, evolution, and phenotypic differences among different species, strains, or clones and to uncover potential virulence genes. Knowledge of the genomes provides the basis for the application of new powerful approaches for the understanding of the biology of the organisms studied.

Although *Legionella* are mainly environmental bacteria, several species are pathogenic to humans, in particular *Legionella pneumophila* (Fraser et al., 1977; Mcdade et al., 1977) and *Legionella longbeachae* (Mckinney et al., 1981). Legionnaires' disease has emerged in the second half of the twentieth century partly due to human alterations of the environment. The development of artificial water systems in the last decades like air conditioning systems, cooling towers, showers, and other aerosolizing devices has allowed *Legionella* to gain access to the human respiratory system. When inhaled in contaminated aerosols, pathogenic *Legionella* can reach the alveoli of the lung where they are subsequently engulfed by macrophages. In contrast to most bacteria, which are destroyed, some *Legionella* species can multiply within the phagosome and eventually kill the macrophage, resulting in a severe, often fatal

pneumonia called legionellosis or Legionnaires' disease (mortality rate of 5–20%; up to 50% in nosocomial infections; Steinert et al., 2002; Marrie, 2008; Whitley and Bentham, 2011). To replicate intracellularly *L. pneumophila* manipulates host cellular processes using bacterial proteins that are delivered into the cytosolic compartment of the host cell by a specialized type IV secretion system called Dot/Icm. The proteins delivered by the Dot/Icm system target host factors implicated in controlling membrane transport in eukaryotic cells, which enables *L. pneumophila* to create an endoplasmic reticulum-like vacuole that supports intracellular replication in both protozoan and mammalian host cells (for a review see Hubber and Roy, 2010).

An interesting epidemiological observation is, that among the over 50 *Legionella* species described today, strains belonging to the species *L. pneumophila* are responsible for over 90% of the legionellosis cases worldwide and strains belonging to the species *L. longbeachae* are responsible for about 5% of human legionellosis cases worldwide (Yu et al., 2002). Surprisingly, this distribution is very different in Australia and New Zealand where *L. pneumophila* accounts for “only” 45.7% of the cases but *L. longbeachae* is implicated in 30.4% of the human cases. Furthermore, among the strains causing Legionnaires' disease, *L. pneumophila* serogroup 1 (Sg1) alone is responsible for over 85% of cases (Yu et al., 2002; Doleans et al., 2004) despite the description of 15 different Sg within this species. In addition, the characterization of over 400

different *L. pneumophila* Sg1 strains has shown that only a minority among these is responsible for causing most of the human disease (Edelstein and Metlay, 2009). Some of these clones are distributed worldwide like *L. pneumophila* strain Paris (Cazalet et al., 2008) others have a more restricted geographical distribution, like the recently described endemic clone, prevalent in Ontario, Canada (Tijet et al., 2010). For the species *L. longbeachae* two serogroups are described to date (Bibb et al., 1981; Mckinney et al., 1981). *L. longbeachae* Sg1 is predominant in human disease as it causes up to 95% of the cases of legionellosis worldwide and most outbreaks and sporadic cases in Australia (Anonymous, 1997; Montanaro-Punzengruber et al., 1999). The two main human pathogenic *Legionella* species, *L. pneumophila* and *L. longbeachae* cause the same disease and symptoms in humans (Amodeo et al., 2009), however, there exist major differences between both species in niche adaptation and host susceptibility.

- (i) They are found in different environmental niches, as *L. pneumophila* is mainly found in natural and artificial water circuits and *L. longbeachae* is principally found in soil and therefore associated with gardening and use of potting compost (O'Connor et al., 2007). However, although less common, the isolation of *L. pneumophila* from potting soil in Europe has also been reported (Casati et al., 2009; Velonakis et al., 2009). Human infection due to *L. longbeachae* is particularly common in Australia but cases have been documented also in other countries like the USA, Japan, Spain, England, or Germany (MMWR, 2000; Garcia et al., 2004; Kubota et al., 2007; Kumpers et al., 2008; Pravinkumar et al., 2010).
- (ii) As described for other *Legionella* species, person to person transmission of *L. longbeachae* has not been documented, however, the primary transmission mode seems to be inhalation of dust from contaminated compost or soil that contains the organism (Steele et al., 1990; MMWR, 2000; O'Connor et al., 2007).
- (iii) Furthermore, for *L. pneumophila* a biphasic life cycle was observed *in vitro* and *in vivo* as exponential phase bacteria do not express virulence factors and are unable to replicate intracellularly. The ability of *L. pneumophila* to replicate intracellularly is triggered at the post-exponential phase by a complex regulatory cascade (Molofsky and Swanson, 2004; Sahr et al., 2009). In contrast, less is known on the *L. longbeachae* intracellular life cycle and its virulence factors. It was recently shown that unlike *L. pneumophila* the ability of *L. longbeachae* to replicate intracellularly is independent of the bacterial growth phase (Asare and Abu Kwaik, 2007) and that phagosome biogenesis is different. Like *L. pneumophila*, the *L. longbeachae* phagosome is surrounded by endoplasmic reticulum and does not mature to a phagolysosome; however it acquires early and late endosomal markers (Asare and Abu Kwaik, 2007).
- (iv) Another interesting difference between these two species is their ability to colonize the lungs of mice. While only A/J mice are permissive for replication of *L. pneumophila*, A/J, C57BL/6, and BALB/c mice are all permissive for replication of *L. longbeachae* (Asare et al., 2007; Gobin et al., 2009). Resistance of C57BL/6 and BALB/c mice to *L. pneumophila*

has been attributed to polymorphisms in Nod-like receptor apoptosis inhibitory protein 5 (*naip5*) allele that recognizes the C-terminus of flagellin (Wright et al., 2003; Molofsky et al., 2006; Ren et al., 2006; Lightfield et al., 2008). The current model is that *L. pneumophila* replication is restricted due to flagellin dependent caspase-1 activation through Naip5-Ipaf and early macrophage cell death by pyroptosis. However, although depletion or inhibition of caspase-1 activity leads to decreased targeting of bacteria to lysosomes, the mechanism of caspase-1-dependent restriction of *L. pneumophila* replication in macrophages and *in vivo* is not fully understood (Schuelein et al., 2011).

In the last years, six genomes of different *L. pneumophila* strains (Paris, Lens, Philadelphia, Corby, Alcoy, and 130b (Cazalet et al., 2004; Chien et al., 2004; Steinert et al., 2007; D'Auria et al., 2010; Schroeder et al., 2010) have been published. The genome sequences of all but strain 130b were completely finished. Furthermore, the sequencing and analysis of four genomes of *L. longbeachae* have been carried out recently (Cazalet et al., 2010). *L. longbeachae* strain NSW150 of Sg1 isolated in Australia from a patient was sequenced completely, and for the remaining three strains (ATCC33462, Sg1 isolated from a human lung, C-4E7 and 98072, both of Sg2 isolated from patients) a draft genome sequence was reported. A fifth *L. longbeachae* strain (D-4968 of Sg1, isolated in the US from a patient) was recently sequenced and the analysis of the genome sequences assembled into 89 contigs was reported (Kozak et al., 2010).

Here we will describe what we learned from the analysis and comparison of the sequenced *Legionella* strains. We will discuss their general characteristics and then highlight the specific features or common traits with respect to the different ecological niches and the differences in host susceptibility of these two *Legionella* species. Emphasis will be put on putative virulence and *Legionella* life cycle related functions. In the last part we will analyze and discuss the possible evolution of the identified virulence factors. Finally, future perspectives in *Legionella* genomics are presented.

GENERAL FEATURES OF THE *L. PNEUMOPHILA* AND *L. LONGBEACHAE* GENOMES

Legionella pneumophila and *L. longbeachae* each have a single, circular chromosome with a size of 3.3–3.5 Mega bases (Mb) for *L. pneumophila* and 3.9–4.1 Mb for *L. longbeachae*. For both the average G + C content is 38% (Tables 1A,B). The *L. pneumophila* strains Paris and Lens each contain different plasmids, 131.9 kb and 59.8 kb in size, respectively. In strain Philadelphia-1, 130b, Alcoy, and Corby no plasmid was identified. The *L. longbeachae* strains NSW10 and D-4986 carry highly similar plasmids of about 70 kb and DNA identity of 99%, strains C-4E7 and 98072 also contain each a highly similar plasmid of 133.8 kb in size. Thus similar plasmids circulate among *L. longbeachae* strains, but they seem to be different from those found in *L. pneumophila*.

A total of ~3000 and 3500 protein-encoding genes are predicted in the *L. pneumophila* and *L. longbeachae* genomes, respectively. No function could be predicted for about 40% of these genes and about 20% are unique to the genus *Legionella*. Comparative analysis of the genome structure of the *L. pneumophila* genomes showed

Table 1 | General features of the sequenced *Legionella* genomes.

A. Complete and draft genomes of <i>L. pneumophila</i> obtained by classical or new generation sequencing						
<i>L. pneumophila</i>						
	Paris	Lens	Philadelphia	Corby	Alcoy	130b ^c
Chromosome size (kb) ^a	3504 (131.9) ^b	3345 (59.8)	3397	3576	3516	3490
G + C content (%)	38.3 (37.4)	38.4 (38)	38.3	38	38.4	38.2
No. of genes ^a	3123 (142)	2980 (60)	3031	3237	3197	3288
No. of protein coding genes ^a	3078 (140)	2921 (60)	2999	3193	3097	3141
Percentage of CDS (%)	87.9	88.0	90.2	86.8	86.0	87.9
No. of specific genes	225	181	213	144	182	386 ^c
No. of 16S/23S/5S	03/03/03	03/03/03	03/03/03	03/03/03	03/03/03	ND
No. transfer RNA	44	43	43	43	43	42
Plasmids	1	1	0	0	0	0
B. Complete and draft genomes of <i>L. longbeachae</i> obtained by classical or new generation sequencing						
<i>L. longbeachae</i>						
	NSW 150	D-4968	ATCC33462	98072	C-4E7	
Chromosome size (Kb)	4077 (71)	4016 (70)	4096	4018 (133.8)	3979 (133.8)	
G + C content (%)	37.1 (38.2)	37.0	37.0	37.0 (37.8)	37 (37.8)	
No. of genes	3660 (75)	3557 (61)	–	–	–	
No. of 16S/23S/5S	04/04/04	04/04/04	04/04/04	04/04/04	04/04/04	
No. of contigs > 0.5–300 kb	Complete	13	64	65	63	
N50 contig size*	Complete	–	138 kb	129 kb	134 kb	
Percentage of coverage**	100%	96.3	96.3	93.4	93.1	
Number of SNP with NSW150	0	1900	1611	16 853	16 820	
Plasmids	1	1	0	1	1	

^aUpdated annotation; CDS, coding sequence; ^bdata from plasmids in parenthesis; ^cThe 130b sequence is not a manually corrected and finished assembly, thus the high number of specific genes might be due to not corrected sequencing errors; ND, not determined; *N50 contig size, calculated by ordering all contig sizes and adding the lengths (starting from the longest contig) until the summed length exceeds 50% of the total length of all contigs (half of all bases reside in a contiguous sequence of the given size or more); SNP, single nucleotide polymorphism; **for SNP detection; – not determined.

high colinearity, with only few translocations, duplications, deletions, or inversions (**Figures 1A,B**) and identified between 6 and 11% of genes as specific to each *L. pneumophila* strain. Principally, the genomes contain three large plasticity zones, where the synteny is disrupted: a 260-kb inversion in strain Lens with respect to strains Paris and Philadelphia-1, a 130-kb fragment which is inserted in a different genomic location in strains Paris and Philadelphia-1 and the about 50 kb chromosomal region carrying the Lvh type IV secretion system, previously described in strain Philadelphia-1 (Segal et al., 1999). Furthermore, deletions and insertions of several smaller regions were identified in each strain, as well as regions with variable gene content. In contrast, comparison of the completed chromosome sequences of *L. pneumophila* and *L. longbeachae* shows that the two *Legionella* species have a significantly different genome organization (**Figure 1C**). Moreover only about 65% of the *L. longbeachae* genes are orthologous to *L. pneumophila* genes, whereas about 34% of all genes are specific to *L. longbeachae* with respect to *L. pneumophila* Paris, Lens, Philadelphia, and Corby (defined by less than 30% amino acid identity over 80% of the length of the smallest protein).

Analysis of single nucleotide polymorphisms (SNP) revealed a very low SNP number of less than 0.4% among the four *L. longbeachae* genomes, which is significantly lower than the polymorphism of about 2% between *L. pneumophila* Sg1 strains Paris

and Philadelphia (**Table 1B**). Comparison of the two *L. longbeachae* Sg1 genomes (NSW150, ATCC33462) identified 1611 SNPs of which 1426 are located in only seven chromosomal regions mainly encoding putative mobile elements, whereas the remaining 185 SNPs were evenly distributed around the chromosome. A similar number of about 1900 SNPs were identified when comparing strains NSW150 to strain D-4968 (**Table 1B**). In contrast, the SNP number between two strains of different Sg was higher, with about 16000 SNPs present between Sg1 and Sg2 strains (**Table 1B**). This low SNP number and relatively homogeneous distribution of the SNPs around the chromosome suggest recent expansion for the species *L. longbeachae* (Cazalet et al., 2010). The sequences and their analysis are accessible at <http://genolist.pasteur.fr/LegioList/>.

To investigate the phylogenetic relationship among the *L. pneumophila* and *L. longbeachae* strains we here used the nucleotide sequence of *recN* (recombination and repair protein-encoding gene) aligned based on the protein alignment. Based on an analysis of 32 protein-encoding genes widely distributed among bacterial genomes, RecN was described as the gene with the greatest potential for predicting genome relatedness at the genus or subgenus level (Zeigler, 2003). As depicted in **Figure 2**, the phylogenetic relationship among the four *L. pneumophila* strains is very high, and *L. longbeachae* is clearly more distant.

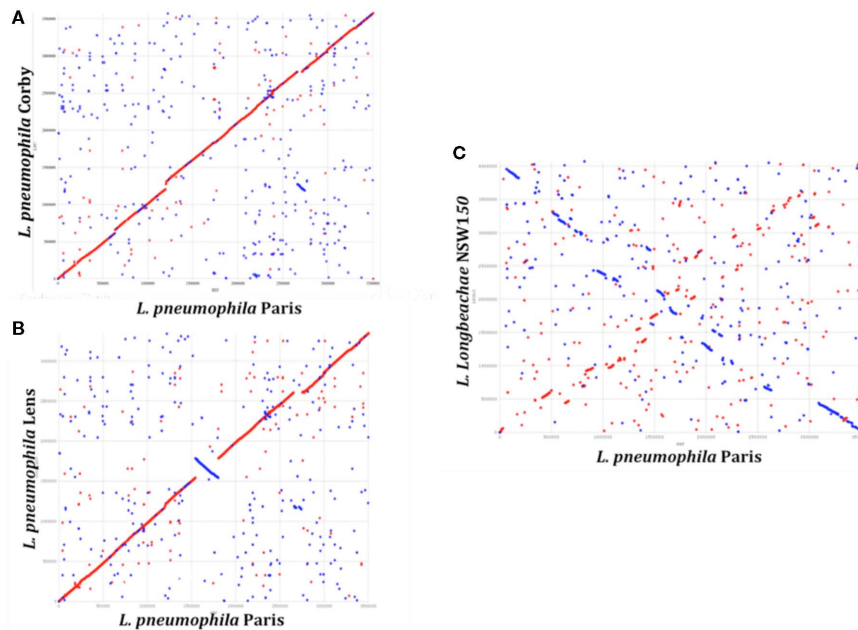


FIGURE 1 | Synteny plot of the chromosomes of *L. pneumophila* strains Paris, Lens, Corby, and *L. longbeachae* NSW150. The plot was created using the mummer software package. **(A)** Synteny plot of the chromosomes of strains *L. pneumophila* Paris and Corby **(B)** and strains *L. pneumophila* Paris and Lens and **(C)** strains *L. pneumophila* Paris and *L. longbeachae* NSW150.

Inversions between the genomic sequences are represented in blue. Genome-wide synteny is disrupted by a 260 kb inversion (blue) and a 130 kb plasticity zone between strain *L. pneumophila* Paris and Lens. In contrast, synteny between *L. pneumophila* and *L. longbeachae* is highly conserved.

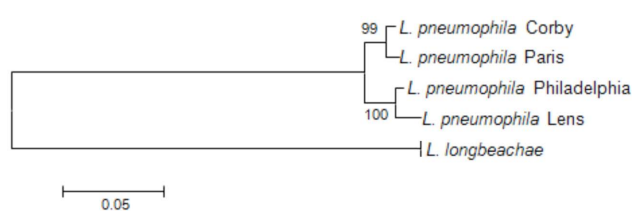


FIGURE 2 | Phylogenetic tree showing the relationship of the sequenced *L. pneumophila* and *L. longbeachae* strains based on the *recN* sequence. The tree was constructed using the *recN* sequences of each genome and the Neighbor joining method in MEGA. *L. longbeachae* is indicated without strain designation, as the *recN* sequence of all sequenced strains is identical and thus only one representative strain is indicated on the tree. Numbers at branching nodes are percentages of 1000 bootstrap replicates.

DIVERSITY IN SECRETION SYSTEMS AND THEIR SUBSTRATES MAY CONTRIBUTE TO DIFFERENCES IN INTRACELLULAR TRAFFICKING AND NICHE ADAPTATION

The capacity of pathogens like *Legionella* to infect eukaryotic cells is intimately linked to the ability to manipulate host cell functions to establish an intracellular niche for their replication. Essential for the ability of *Legionella* to subvert host functions are its different secretion systems. The two major ones, known to be involved in virulence of *L. pneumophila* are the Dot/Icm type IV secretion system (T4SS) and the Lsp type II secretion system (T2SS; Marra et al., 1992; Berger and Isberg, 1993; Rossier and Cianciotto, 2001).

For *L. pneumophila* type II protein secretion is critical for infection of amoebae, macrophages and mice. Analyses of the *L. longbeachae* genome sequences showed, that it contains all genes to encode a functional Lsp type II secretion machinery (Cazalot et al., 2010; Kozak et al., 2010). Several studies, including the analysis of the *L. pneumophila* type II secretome indicated that *L. pneumophila* encodes at least 25 type II secreted substrates (Debroy et al., 2006; Cianciotto, 2009). Although this experimentally defined repertoire of type II secretion-dependent proteins is the largest known in bacteria, it may contain even more than 60 proteins as 35 additional proteins with a signal sequence were identified by *in silico* analyses (Cianciotto, 2009). A search for homologs of these substrates in the *L. longbeachae* genome sequences revealed that 9 (36%) of the 25 type II secretion system substrates described for *L. pneumophila* are absent from *L. longbeachae* (Table 2). For example the phospholipase C encoded by *plcA* and the *chiA*-encoded chitinase, which was shown to promote *L. pneumophila* persistence in the lungs of A/J mice are not present in *L. longbeachae* (Debroy et al., 2006). Thus over a third of the T2SS substrates seem to differ between *L. pneumophila* and *L. longbeachae*, a feature probably related to the different ecological niches occupied, but also to different virulence properties in the hosts.

Indispensable for replication of *L. pneumophila* in the eukaryotic host cells is the Dot/Icm T4SS (Nagai and Kubori, 2011), which translocate a large repertoire of bacterial effectors into the host cell. These effectors modulate multiple host cell processes and in particular, redirect trafficking of the *L. pneumophila* phagosome and mediate its conversion into an ER-derived organelle competent for

Table 2 | Distribution of type II secretion-dependent proteins of *L. pneumophila* in *L. longbeachae*.

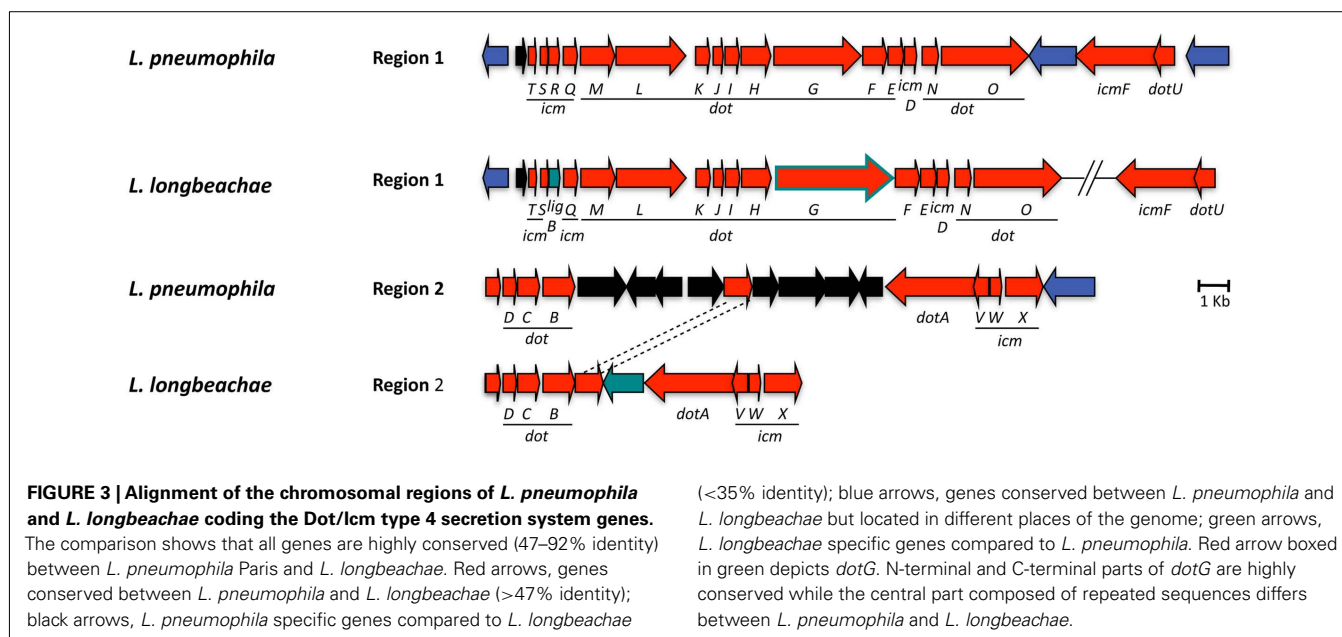
<i>L. pneumophila</i>						<i>L. longbeachae</i>		Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b*	NSW	D-4968		
<i>lpg0467</i>	<i>lpp0532</i>	<i>lpl0508</i>	<i>lpc2877</i>	<i>lpa00713</i>	<i>lpw05741</i>	<i>llo2721</i>	<i>llb2607</i>	<i>proA</i>	Zinc metalloprotease, promotes amebal infection
<i>lpg1119</i>	<i>lpp1120</i>	<i>lpl1124</i>	<i>lpc0577</i>	<i>lpa01742</i>	–	<i>llo1016</i>	<i>llb0700</i>	<i>map</i>	Tartrate-sensitive acid phosphatase
<i>lpg2343</i>	<i>lpp2291</i>	<i>lpl2264</i>	<i>lpc1811</i>	<i>lpa03353</i>	<i>lpw25361</i>	<i>llo2819</i>	<i>llb2504</i>	<i>plaA</i>	Lysophospholipase A
<i>lpg2837</i>	<i>lpp2894</i>	<i>lpl2749</i>	<i>lpc3121</i>	<i>lpa04118</i>	<i>lpw30971</i>	<i>llo0210</i>	<i>llb1661</i>	<i>plaC</i>	Glycerophospholipid:cholesterol transferase
<i>lpg0502</i>	<i>lpp0565</i>	<i>lpl0541</i>	<i>lpc2843</i>	<i>lpa00759</i>	<i>lpw05821</i>	–	–	<i>plcA</i>	Phospholipase C
<i>lpg0745</i>	<i>lpp0810</i>	<i>lpl0781</i>	<i>lpc2548</i>	<i>lpa01148</i>	<i>lpw08251</i>	<i>llo2076</i>	<i>llb3335</i>	<i>lipA</i>	Mono- and triacylglycerol lipase
<i>lpg1157</i>	<i>lpp1159</i>	<i>lpl1164</i>	<i>lpc0620</i>	<i>lpa01801</i>	<i>lpw12111</i>	<i>llo2433</i>	<i>llb2928</i>	<i>lipB</i>	Triacylglycerol lipase
<i>lpg2848</i>	<i>lpp2906</i>	<i>lpl2760</i>	<i>lpc3133</i>	<i>lpa04141</i>	<i>lpw31111</i>	<i>llo0201</i>	<i>llb1671</i>	<i>smA</i>	Type 2 ribonuclease, promotes amebal infection
<i>lpg1116</i>	<i>lpp1117</i>	<i>lpl1121</i>	<i>lpc0574</i>	<i>lpa01738</i>	<i>lpw11641</i>	–	–	<i>chiA</i>	Chitinase, promotes lung infection
<i>lpg2814</i>	<i>lpp2866</i>	<i>lpl2729</i>	<i>lpc3100</i>	<i>lpa04088</i>	<i>lpw30701</i>	<i>llo0255</i>	<i>llb1611</i>	<i>lapA</i>	Leucine, phenylalanine, and tyrosine aminopeptidase
<i>lpg0032</i>	<i>lpp0031</i>	<i>lpl0032</i>	<i>lpc0032</i>	<i>lpa00041</i>	<i>lpw00321</i>	–	–	<i>lapB</i>	Lysine and arginine aminopeptidase
<i>lpg0264</i>	<i>lpp0335</i>	<i>lpl0316</i>	<i>lpc0340</i>	<i>lpa00461</i>	<i>lpw03521</i>	<i>llo3103</i>	<i>llb2271</i>		Weakly similar to bacterial amidase
<i>lpg2622</i>	<i>lpp2675</i>	<i>lpl2547</i>	<i>lpc0519</i>	<i>lpa03836</i>	<i>lpw28341</i>	–	–		Weakly similar to bacterial cysteine protease
<i>lpg1918</i>	<i>lpp1893</i>	<i>lpl1882</i>	<i>lpc1372</i>	<i>lpa02774</i>	<i>lpw19571</i>	<i>llo3308</i>	<i>llb2032</i>	<i>celA</i>	Endoglucanase
<i>lpg2999</i>	<i>lpp3071</i>	<i>lpl2927</i>	<i>lpc3315</i>	<i>lpa04395</i>	<i>lpw32851</i>	–	–		Predicted astacin-like zink endopeptidase
<i>lpg2644</i>	<i>lpp2697</i>	<i>lpl2569</i>	<i>lpc0495</i>	<i>lpa03870</i>	–	–	–		Some similarity to collagen like protein
<i>lpg1809</i>	<i>lpp1772</i>	<i>lpl1773</i>	<i>lpc1253</i>	<i>lpa02614</i>	<i>lpw18401</i>	<i>llo1104</i>	<i>llb0603</i>		Unknown
<i>lpg1385</i>	<i>lpp1340</i>	<i>lpl1336</i>	<i>lpc0801</i>	<i>lpa02037</i>	<i>lpw13951</i>	<i>llo1474</i>	<i>llb0177</i>		Unknown
<i>lpg0873</i>	<i>lpp0936</i>	<i>lpl0906</i>	<i>lpc2419</i>	<i>lpa01320</i>	<i>lpw09571</i>	<i>llo2475</i>	<i>llb2883</i>		Unknown
<i>lpg0189</i>	<i>lpp0250</i>	<i>lpl0249</i>	<i>lpc0269</i>	<i>lpa00360</i>	<i>lpw02811</i>	–	–		Unknown
<i>lpg0956</i>	<i>lpp1018</i>	<i>lpl0958</i>	<i>lpc2331</i>	<i>lpa01443</i>	<i>lpw10421</i>	<i>llo1935</i>	<i>llb3498</i>		Unknown
<i>lpg2689</i>	<i>lpp2743</i>	<i>lpl2616</i>	<i>lpc0447</i>	<i>lpa03925</i>	<i>lpw29431</i>	<i>llo0361</i>	<i>llb1497</i>	<i>icmX</i>	Linked to Dot/Icm type IV secretion genes
<i>lpg1244</i>	<i>lpp0181</i>	<i>lpl0163</i>	–	–	<i>lpw01541</i>	–	–	<i>lvrE</i>	Linked to Lvh type IV secretion genes
<i>lpg1832</i>	<i>lpp1795</i>	<i>lpl1796</i>	<i>lpc1276</i>	<i>lpa02647</i>	<i>lpw18641</i>	<i>llo1152</i>	<i>llb0546</i>		Weakly similar to VirK
<i>lpg1962</i>	<i>lpp1946</i>	<i>lpl1936</i>	<i>lpc1440</i>	<i>lpa02861</i>	<i>lpw20131</i>	–	–		Putative peptidyl-prolyl cis-trans isomerase
<i>lpg0422</i>	<i>lpp0489</i>	<i>lpl0465</i>	<i>lpc2921</i>	<i>lpa0657</i>	<i>lpw05041</i>	<i>llo2801</i>	<i>llb2523</i>	<i>gamA</i>	Glucoamylase

Substrates in this list are according to Cianciotto (2009); *strain 130b is not a finished sequence and not manually curated. Thus absence of a substrate can also be due to gaps in the sequence; – means not present; NSW means *L. longbeachae* NSW150.

intracellular bacterial replication (Shin and Roy, 2008; Cianciotto, 2009). The Dot/Icm system is conserved in *L. longbeachae* with a similar gene organization and protein identities of 47–92% with respect to *L. pneumophila* (Figure 3). This is similar to what has been reported previously for other *Legionella* species (Morozova et al., 2004). The only major differences identified are that in *L. longbeachae* the *icmR* gene is replaced by the *ligB* gene, however, the encoded proteins have been shown to perform similar functions (Feldman and Segal, 2004; Feldman et al., 2005) and that the DotG/IcmE protein of *L. longbeachae* (1525 aa) is 477 amino acids larger than that of *L. pneumophila* (1048 aa; Cazalet et al., 2010). DotG of *L. pneumophila* is part of the core transmembrane complex of the secretion system and is composed of three domains: a transmembrane N-terminal domain, a central region composed of 42 repeats of 10 amino acid and a C-terminal region homologous to VirB10. In contrast, the central region of *L. longbeachae* DotG is composed of approximately 90 repeats. Among the many VirB10 homologs present in bacteria, the *Coxiella* DotG and the *Helicobacter pylori* Cag7 are the only ones, which also have multiple repeats of 10 aa (Segal et al., 2005). It will be challenging to understand the impact of this modification on the function of the type IV secretion system. A *L. longbeachae* T4SS mutant obtained

by deleting the *dotA* gene is strongly attenuated for intracellular growth in *Acanthamoeba castellanii* and human macrophages (Cazalet et al., 2010, and unpublished data), is outcompeted by the wild type strain 24 and 72 h after infection of lungs of A/J mice and is also dramatically attenuated for replication in lungs of A/J mice upon single infections (Cazalet et al., 2010). Thus, similar to what is seen for *L. pneumophila*, the Dot/Icm T4SS of *L. longbeachae* is also central for its pathogenesis and the capacity to replicate in eukaryotic host cells.

This T4SS is crucial for intracellular replication for *Legionella* as it secretes an exceptionally large number of proteins into the host cell. Using different methods, 275 substrates have been shown to be translocated in the host cell in a Dot/Icm T4SS dependent manner (Campodonico et al., 2005; De Felipe et al., 2005, 2008; Shohdy et al., 2005; Burstein et al., 2009; Heidtman et al., 2009; Zhu et al., 2011). Table 3 shows the distribution of the 275 Dot/Icm substrates identified in *L. pneumophila* strain Philadelphia and their distribution in the six *L. pneumophila* and five *L. longbeachae* genomes sequenced. Their conservation among different *L. pneumophila* strains is very high, as over 80% of the substrates are present in all *L. pneumophila* strains analyzed here. In contrast, the search for homologs of these *L. pneumophila* Dot/Icm



substrates in *L. longbeachae* showed that even more pronounced differences are present than in the repertoire of type II secreted substrates. Only 98 of these 275 *L. pneumophila* Dot/Icm substrates have homologs in the *L. longbeachae* genomes (Table 3). However, the repertoire of *L. longbeachae* substrates seems also to be quite large, as a search for proteins that encode eukaryotic like domains and contain the secretion signal described by Nagai et al. (2005) and the additional criteria defined by Kubori et al. (2008) predicted 51 putative Dot/Icm substrates specific for *L. longbeachae* NSW150 (Cazalet et al., 2010) indicating that at least over 140 proteins might be secreted by the Dot/Icm T4SS of *L. longbeachae*. A similar number of *L. longbeachae* specific putative eukaryotic like proteins and effectors was predicted for strain D-4968 (Kozak et al., 2010). Examples of effector proteins conserved between the two species are RalF, VipA, VipF, SidC, SidE, SidJ, YlfA, LepA, and LepB, which contribute to trafficking or recruitment and retention of vesicles to *L. pneumophila* (Nagai et al., 2002; Chen et al., 2004; Luo and Isberg, 2004; Campodonico et al., 2005; Shohdy et al., 2005; Liu and Luo, 2007). It is interesting to note that homologs of SidM/DrrA and SidD are absent from *L. longbeachae* but a homolog of LepB is present. For *L. pneumophila* it was shown that SidM/DrrA, SidD, and LepB act in cooperation to manipulate Rab1 activity in the host cell. DrrA/SidM possesses three domains, an N-terminal AMP-transfer domain (AT), a nucleotide exchange factor (GEF) domain in the central part and a phosphatidylinositol-4-Phosphate binding domain (P4M) in its C-terminal part. After association of DrrA/SidM with the membrane of the *Legionella*-containing vacuole (LCV) via P4M (Brombacher et al., 2009), it recruits Rab1 via the GEF domain and catalyzes the GDP–GTP exchange (Ingmundson et al., 2007; Machner and Isberg, 2007). Rab1 is then adenylated by the AT domain leading to inhibition of GAP-catalyzed Rab1-deactivation (Müller et al., 2010). LepB cannot bind AMPylated Rab1 (Ingmundson et al., 2007). Recently it was shown that SidD deAMPylates Rab1 and enables LepB to bind Rab1 to promote

its GTP–GDP exchange (Neunuebel et al., 2011; Tan and Luo, 2011). One might assume that other proteins of *L. longbeachae* not yet identified may perform the functions of DrrA/SidM and SidD. Another interesting observation is, that all except four of the effector proteins of *L. pneumophila* that are conserved in *L. longbeachae* are also conserved in all sequenced *L. pneumophila* genomes (Table 3).

Taken together the T2SS Lsp and the T4SS Dot/Icm are highly conserved between *L. pneumophila* and *L. longbeachae*. However, more than a third of the known *L. pneumophila* type II- and over 70% of type IV-dependent substrates differ between both species. These species specific, secreted effectors might be implicated in the different niche adaptations and host susceptibilities. Most interestingly, of the 98 *L. pneumophila* substrates conserved in *L. longbeachae* 87 are also present in all *L. pneumophila* strains sequenced to date. Thus, these 87 Dot/Icm substrates might be essential for intracellular replication of *Legionella* and represent a minimal toolkit for intracellular replication that has been acquired before the divergence of the two species.

MOLECULAR MIMICRY IS A MAJOR VIRULENCE STRATEGY OF *L. PNEUMOPHILA* AND *L. LONGBEACHAE*

The *L. pneumophila* genome sequence analysis has revealed that many of the predicted or experimentally verified Dot/Icm secreted substrates are proteins similar to eukaryotic proteins or contain motifs mainly or only found in eukaryotic proteins (Cazalet et al., 2004; De Felipe et al., 2005). Thus comparative genomics suggested that *L. pneumophila* encodes specific virulence factors that have evolved during its evolution with eukaryotic host cells such as fresh-water amoeba (Cazalet et al., 2004). The protein-motifs predominantly found in eukaryotes, which were identified in the *L. pneumophila* genomes are ankyrin repeats, SEL1 (TPR), Set domain, Sec7, serine threonine kinase domains (STPK), U-box, and F-box motifs. Examples for eukaryotic like proteins of *L. pneumophila* are two secreted apyrases, a

Table 3 | Distribution of 275 Dot/Icm substrates identified in strain *L. pneumophila* Philadelphia in the 5 sequenced *L. pneumophila* and 5 sequenced *L. longbeachae* strains.

L. pneumophila						L. longbeachae					Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b	NSW 150 D-4968	AT	98072	C-4E7			
lpg0008	lpp0008	lpl0008	lpc0009	lpa0011	lpw00071	–	–	–	–	–	ravA	Unknown
lpg0012	lpp0012	lpl0012	lpc0013	lpa0016	lpw00111	–	–	–	–	–	cegC1	Ankyrin
lpg0021	lpp0021	lpl0022	lpc0022	lpa0030	lpw00221	llo0047	llb1841	+	+	+	–	Unknown
lpg0030	lpp0030	lpl0031	lpc0031	lpa0040	lpw00311	–	–	–	–	–	ravB	Unknown
lpg0038	lpp0037	lpl0038	lpc0039	lpa0049	lpw00381	–	–	–	–	–	ankQ/ legA10	Ankyrin repeat
lpg0041	–	–	lpc0042	lpa0056	–	–	–	–	–	–	–	Putative metalloprotease
lpg0045	lpp0046	lpl0044	lpc0047	lpa0060	lpw00441	–	–	–	–	–	–	Unknown
lpg0046	lpp0047	lpl0045	lpc0048	lpa0062	lpw00451	–	–	–	–	–	–	Unknown
lpg0059	lpp0062	lpl0061	lpc0068	lpa0085	lpw00621	–	–	–	–	–	ceg2	Unknown
lpg0080	lpp0094	–	–	lpa3018	lpw00781	–	–	–	–	–	ceg3	Unknown
lpg0081	lpp0095	–	–	–	lpw00791	–	–	–	–	–	–	Unknown
lpg0090	lpp0104	lpl0089	lpc0109	lpa0132	lpw00881	–	–	–	–	–	lem1	Unknown
lpg0096	lpp0110	lpl0096	lpc0115	lpa0145	lpw00961	llo1322	llb0347	+	+	+	ceg4	Unknown
lpg0103	lpp0117	lpl0103	lpc0122	lpa0152	lpw01031	llo3312	llb2028	+	+	+	vipF	N-terminal acetyl- transferase, GNAT
lpg0126	lpp0140	lpl0125	lpc0146	lpa0185	lpw01261	–	–	–	–	–	cegC2	Ninein
lpg0130	lpp0145	lpl0130	lpc0151	lpa0194	lpw01311	llo3270	llb2073	+	+	+	–	Unknown
lpg0135	lpp0150	lpl0135	lpc0156	lpa0204	lpw01361	llo2439	llb2921	+	+	+	sdhB	Unknown
lpg0160	lpp0224	lpl0224	lpc0242	lpa0322	lpw02541	–	–	–	–	–	ravD	Unknown
lpg0170	lpp0232	lpl0233	lpc0251	lpa0335	lpw02641	llo1378	llb0280	+	+	+	ravC	Unknown
lpg0171	lpp0233	lpl0234	–	–	lpw02651	–	–	–	–	–	legU1	F-box motif
lpg0172	lpp0234	–	lpc0253	lpa0339	lpw02661	–	–	–	–	–	–	Unknown
lpg0181	lpp0245	lpl0244	lpc0265	lpa0388	lpw02761	llo2453	llb2907	+	+	+	–	Unknown
lpg0191	lpp0251	–	–	–	lpw02821	–	–	–	–	–	ceg5	Unknown
lpg0195	lpp0253	lpl0251	lpc0272	lpa0339	lpw02851	–	–	–	–	–	ravE	Unknown
lpg0196	lpp0254	lpl0252	–	–	lpw02861	llo2549	llb2798	+	+	+	ravF	Unknown
lpg0210	lpp0269	lpl0264	lpc0285	lpa0388	lpw02981	–	–	–	–	–	ravG	Unknown
lpg0227	lpp0286	lpl0281	lpc0303	lpa0412	lpw03151	llo2491	llb2864	+	+	+	ceg7	Unknown
lpg0234	lpp0304	lpl0288	lpc0309	lpa0419	lpw03221	llo0425	llb1431	+	+	+	sidE/laiD	Unknown
lpg0240	lpp0310	lpl0294	lpc0316	lpa0428	lpw03291	llo1601	llb0040	+	+	+	ceg8	Unknown
lpg0246	lpp0316	lpl0300	lpc0323	lpa0436	lpw03361	–	–	–	–	–	ceg9	Unknown
lpg0257	lpp0327	lpl0310	lpc0334	lpa0450	lpw03461	llo2362	llb3009	+	+	+	sdeA	Multidrug resistance protein
lpg0260	lpp0332	lpl0313	lpc0337	lpa0456	lpw03491	–	–	–	–	–	–	Unknown
lpg0275	lpp0349	lpl0327	lpc0351/ 3529	lpa0477	lpw03641	–	–	–	–	–	sdbA	Unknown
lpg0276	lpp0350	lpl0328	lpc0353	lpa0479	lpw03651	llo0327	llb1533	+	+	+	legG2	Ras guanine nucleotide exchange factor
lpg0284	lpp0360	lpl0336	lpc0361	lpa0490	lpw03741	–	–	–	–	–	ceg10	Unknown
lpg0285	lpp0361	lpl0337	lpc0362	lpa0492	lpw03751	–	–	–	–	–	lem2	Unknown
lpg0294	lpp0372	lpl0347	lpc0373	lpa0508	lpw03861	llo0464	llb1386	+	+	+	–	Unknown
lpg0364	lpp0429	lpl0405	lpc2980	lpa0578	lpw04431	–	–	–	–	–	–	Unknown
lpg0365	lpp0430	lpl0406	lpc2979	lpa0580	lpw04441	llo0525	llb1334	+	+	+	–	Unknown
lpg0375	lpp0442	lpl0418	lpc2968	lpa0596	–	–	–	–	–	–	–	Unknown
lpg0376	lpp0443	lpl0419	lpc2967	lpa0597	lpw04591	llo0548	llb1307	+	+	+	sdhA	GRIP, coiled-coil
lpg0390	lpp0457	lpl0433	lpc2954	lpa0613	lpw04721	–	–	–	–	–	vipA	Unknown
lpg0401	lpp0468	lpl0444	lpc2942	lpa0629	lpw04831	llo2582	llb2763	+	+	+	legA7/ceg	Unknown

(Continued)

Table 3 | Continued

<i>L. pneumophila</i>						<i>L. longbeachae</i>					Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b	NSW 150	D-4968	AT	98072	C-4E7		
<i>lpg0402</i>	–	–	–	–	–	–	–	–	–	–	<i>ankY/legA9</i>	Ankyrin, STPK
<i>lpg0403</i>	<i>lpp0469</i>	<i>lpl0445</i>	<i>lpc2941</i>	<i>lpa0630</i>	<i>lpw04841</i>	–	–	–	–	–	<i>ankG/ankZ/legA7</i>	Ankyrin
<i>lpg0405</i>	<i>lpp0471</i>	<i>lpl0447</i>	<i>lpc2939</i>	<i>lpa0633</i>	<i>lpw04861</i>	<i>llo2845</i>	<i>llb2472</i>	+	+	+	–	Spectrin domain
<i>lpg0422</i>	<i>lpp0489</i>	<i>lpl0465</i>	<i>lpc2921</i>	<i>lpa0657</i>	<i>lpw05041</i>	<i>llo2801</i>	<i>llb2523</i>	+	+	+	<i>legY</i>	Putative Glucan 1,4-alpha- glucosidase
<i>lpg0436</i>	<i>lpp0503</i>	<i>lpl0479</i>	<i>lpc2906</i>	<i>lpa0673</i>	<i>lpw05181</i>	–	–	–	–	–	<i>ankJ/legA11</i>	Ankyrin
<i>lpg0437</i>	<i>lpp0504</i>	<i>lpl0480</i>	<i>lpc2905</i>	<i>lpa0674</i>	<i>lpw05191</i>	–	–	–	–	–	<i>ceg14</i>	Unknown
<i>lpg0439</i>	<i>lpp0505</i>	<i>lpl0481</i>	<i>lpc2904</i>	<i>lpa0678</i>	<i>lpw05201</i>	<i>llo2983</i>	<i>llb2392</i>	+	+	+	<i>ceg15</i>	Unknown
<i>lpg0483</i>	<i>lpp0547</i>	<i>lpl0523</i>	<i>lpc2861</i>	<i>lpa0739</i>	<i>lpw05631</i>	<i>llo2705</i>	<i>llb2623</i>	+	+	+	<i>ankC/legA12</i>	Ankyrin
<i>lpg0515</i>	<i>lpp0578</i>	<i>lpl0554</i>	<i>lpc2829</i>	<i>lpa0776</i>	<i>lpw05951</i>	<i>llo3224</i>	<i>llb2129</i>	+	+	+	<i>legD2</i>	Phytanoyl-CoA dioxygenase domain
<i>lpg0518</i>	<i>lpp0581</i>	<i>lpl0557</i>	<i>lpc2826</i>	<i>lpa0781</i>	<i>lpw05981</i>	–	–	–	–	–	–	Unknown
<i>lpg0519</i>	–	–	–	–	–	–	–	–	–	–	<i>ceg17</i>	Unknown
<i>lpg0621</i>	<i>lpp0675</i>	<i>lpl0658</i>	<i>lpc2673</i>	<i>lpa0975</i>	<i>lpw06951</i>	–	–	–	–	–	<i>sidA</i>	Unknown
<i>lpg0634</i>	<i>lpp0688</i>	<i>lpl0671</i>	<i>lpc2660</i>	<i>lpa0996</i>	<i>lpw07081</i>	<i>llo2574</i>	<i>llb2771</i>	+	+	+	–	Unknown
<i>lpg0642</i>	<i>lpp0696/97</i>	<i>lpl0679</i>	<i>lpc2651</i>	<i>lpa1005</i>	<i>lpw07161</i>	–	–	–	–	–	<i>wipB</i>	Unknown
<i>lpg0695</i>	<i>lpp0750</i>	<i>lpl0732</i>	<i>lpc2599</i>	<i>lpa1082</i>	<i>lpw07721</i>	–	–	–	–	–	<i>ankN/ankX/legA8</i>	Ankyrin
<i>lpg0696</i>	<i>lpp0751</i>	<i>lpl0733</i>	<i>lpc2598</i>	<i>lpa1084</i>	<i>lpw07731</i>	–	–	–	–	–	<i>lem3</i>	Unknown
<i>lpg0716</i>	<i>lpp0782</i>	<i>lpl0753</i>	<i>lpc2577</i>	<i>lpa1108</i>	<i>lpw07931</i>	–	–	–	+	+	–	Unknown
<i>lpg0733</i>	<i>lpp0799</i>	<i>lpl0770</i>	<i>lpc2559</i>	<i>lpa1135</i>	<i>lpw08111</i>	<i>llo0831</i>	<i>llb0892</i>	+	+	+	<i>ravH</i>	Unknown
<i>lpg0796</i>	<i>lpp0859</i>	–	–	–	–	–	–	–	–	–	–	Unknown
<i>lpg0898</i>	<i>lpp0959</i>	<i>lpl0929</i>	<i>lpc2395</i>	<i>lpa1360</i>	<i>lpw09801</i>	–	–	–	–	–	<i>ceg18</i>	Unknown
<i>lpg0926</i>	<i>lpp0988</i>	<i>lpl0957</i>	<i>lpc2365</i>	<i>lpa1397</i>	<i>lpw10111</i>	–	–	–	–	–	<i>ravI</i>	Unknown
<i>lpg0940</i>	<i>lpp1002</i>	<i>lpl0971</i>	<i>lpc2349</i>	<i>lpa1415</i>	<i>lpw10251</i>	–	–	–	–	–	<i>lidA</i>	Unknown
<i>lpg0944</i>	<i>lpp1006</i>	–	<i>lpc2345</i>	<i>lpa1421</i>	–	–	–	–	–	–	<i>ravJ</i>	Unknown
<i>lpg0945</i>	<i>lpp1007</i>	<i>lpl1579</i>	<i>lpc2344</i>	<i>lpa1423</i>	<i>lpw10311</i>	–	–	–	–	–	<i>legL1</i>	LLR
<i>lpg0963</i>	<i>lpp1025</i>	<i>lpl0992</i>	<i>lpc2324</i>	<i>lpa1453</i>	<i>lpw10491</i>	<i>llo0934</i>	<i>llb0782</i>	+	+	+	–	Unknown
<i>lpg0967</i>	<i>lpp1029</i>	–	<i>lpc2320</i>	<i>lpa1459</i>	<i>lpw10531</i>	–	–	–	–	–	–	Unknown
<i>lpg0968</i>	<i>lpp1030</i>	<i>lpl0997</i>	<i>lpc2319</i>	<i>lpa1460</i>	<i>lpw10541</i>	–	–	–	–	–	<i>sidK</i>	Unknown
<i>lpg0969</i>	<i>lpp1031</i>	<i>lpl0998</i>	<i>lpc2318</i>	<i>lpa1461</i>	<i>lpw10551</i>	<i>llo3265</i>	<i>llb2078</i>	+	+	+	<i>ravK</i>	Unknown
<i>lpg1083</i>	–	–	–	–	–	–	–	–	–	–	–	Unknown
<i>lpg1101</i>	<i>lpp1101</i>	<i>lpl1100</i>	<i>lpc2154*</i>	<i>lpa1709</i>	<i>lpw11451</i>	–	–	–	–	–	<i>lem4</i>	Unknown
<i>lpg1106</i>	<i>lpp1105</i>	<i>lpl1105</i>	<i>lpc2149</i>	<i>lpa1719</i>	<i>lpw11501</i>	<i>llo1414</i>	<i>llb0239/41</i>	+	+	+	–	Unknown
<i>lpg1108</i>	<i>lpp1108</i>	<i>lpl1108</i>	<i>lpc2146</i>	<i>lpa1724</i>	<i>lpw11531</i>	<i>llo3030</i>	<i>llb2350</i>	+	+	+	<i>ravL</i>	Unknown
<i>lpg1109</i>	<i>lpp1109</i>	–	<i>lpc2145</i>	<i>lpa1725</i>	–	–	–	–	–	–	<i>ravM</i>	Unknown
<i>lpg1110</i>	<i>lpp1111</i>	<i>lpl1114</i>	<i>lpc2142</i>	<i>lpa1728</i>	<i>lpw11571</i>	–	–	–	–	–	<i>lem5</i>	Unknown
<i>lpg1111</i>	<i>lpp1112</i>	<i>lpl1115</i>	<i>lpc2141</i>	<i>lpa1730</i>	<i>lpw11581</i>	<i>llo3126</i>	<i>llb2244</i>	+	+	+	<i>ravN</i>	Unknown
<i>lpg1120</i>	–	–	–	–	<i>lpw11681</i>	–	–	–	–	–	<i>lem6</i>	Unknown
<i>lpg1121</i>	<i>lpp1121</i>	<i>lpl1126</i>	<i>lpc0578</i>	<i>lpa1743</i>	<i>lpw11691</i>	<i>llo1321</i>	<i>llb0348</i>	+	+	+	<i>ceg19</i>	Unknown
<i>lpg1124</i>	<i>lpp1125</i>	<i>lpl1129</i>	<i>lpc0582</i>	<i>lpa1748</i>	<i>lpw11741</i>	<i>llo3206</i>	<i>llb2150</i>	+	+	+	–	Unknown
<i>lpg1129</i>	<i>lpp1130</i>	–	–	–	<i>lpw11801</i>	–	–	–	–	–	<i>ravO</i>	Unknown
<i>lpg1137</i>	<i>lpp1139</i>	<i>lpl1144</i>	<i>lpc0601</i>	<i>lpa1776</i>	<i>lpw11901</i>	<i>llo2404</i>	<i>llb2962</i>	+	+	+	–	Unknown
<i>lpg1144</i>	<i>lpp1146</i>	<i>lpl1150</i>	<i>lpc0607</i>	<i>lpa1785</i>	<i>lpw11971</i>	–	–	–	–	–	<i>cegC3</i>	Unknown
<i>lpg1145</i>	<i>lpp1147</i>	<i>lpl1151</i>	<i>lpc0608</i>	<i>lpa1787</i>	<i>lpw11981</i>	–	–	–	–	–	<i>lem7</i>	Unknown
<i>lpg1147</i>	<i>lpp1149</i>	<i>lpl1153</i>	<i>lpc0610</i>	<i>lpa1789</i>	<i>lpw12001</i>	–	–	–	–	–	–	GCN5-related N- acetyltransferase
<i>lpg1148</i>	<i>lpp1150</i>	<i>lpl1154</i>	<i>lpc0611</i>	<i>lpa1790</i>	<i>lpw12011</i>	–	–	–	–	–	–	Unknown
<i>lpg1152</i>	<i>lpp1154</i>	<i>lpl1159</i>	<i>lpc0615</i>	<i>lpa1795</i>	<i>lpw12061</i>	–	–	–	–	–	<i>ravP</i>	Unknown

(Continued)

Table 3 | Continued

<i>L. pneumophila</i>						<i>L. longbeachae</i>					Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b	NSW 150	D-4968	AT	98072	C-4E7		
<i>lpg1154</i>	<i>lpp1156</i>	<i>lpl1161</i>	<i>lpc0617</i>	<i>lpa1797</i>	<i>lpw12081</i>	<i>llo2487</i>	<i>llb2868</i>	+	+	+	<i>ravQ</i>	Unknown
<i>lpg1158</i>	<i>lpp1160</i>	<i>lpl1165*</i>	<i>lpc0621</i>	<i>lpa1802</i>	<i>lpw12121</i>	–	–	–	–	–	–	Unknown
<i>lpg1166</i>	<i>lpp1168</i>	<i>lpl1174</i>	<i>lpc0631</i>	<i>lpa1819</i>	<i>lpw12211</i>	<i>llo1034</i>	<i>llb0680</i>	+	+	+	<i>ravR</i>	Unknown
<i>lpg1171</i>	<i>lpp1173</i>	<i>lpl1179</i>	<i>lpc0637</i>	<i>lpa1826</i>	–	–	–	–	–	–	–	Spectrin domain
<i>lpg1183</i>	<i>lpp1186</i>	<i>lpl1192</i>	<i>lpc0650</i>	<i>lpa1839</i>	<i>lpw12401</i>	<i>llo2390</i>	<i>llb2978</i>	+	+	+	<i>ravS</i>	Unknown
<i>lpg1227</i>	<i>lpp1235</i>	<i>lpl1235</i>	<i>lpc0696</i>	<i>lpa1899</i>	<i>lpw12861</i>	–	–	–	–	–	<i>vpdB</i>	Unknown
<i>lpg1273</i>	<i>lpp1236</i>	<i>lpl1236</i>	<i>lpc0698</i>	<i>lpa1901</i>	<i>lpw12871</i>	–	–	–	–	–	–	Unknown
<i>lpg1290</i>	<i>lpp1253</i>	–	–	–	–	–	–	–	–	–	<i>lem8</i>	Unknown
<i>lpg1312</i>	–	–	–	–	<i>lpw13261</i>	–	–	–	–	–	<i>legC1</i>	Unknown
<i>lpg1316</i>	–	–	–	–	–	<i>llo1389</i>	<i>llb0269</i>	+	+	+	<i>ravT</i>	Unknown
<i>lpg1317</i>	–	–	–	–	–	–	–	–	–	–	<i>ravW</i>	Unknown
<i>lpg1328</i>	<i>lpp1283</i>	<i>lpl1282</i>	<i>lpc0743</i>	<i>lpa1958</i>	–	–	–	–	–	–	<i>legT</i>	Thaumatin domain
<i>lpg1355</i>	<i>lpp1309</i>	–	–	–	–	–	–	–	–	–	<i>sidG</i>	Coiled-coil
<i>lpg1426</i>	<i>lpp1381</i>	<i>lpl1377</i>	<i>lpc0842</i>	<i>lpa2090</i>	<i>lpw14431</i>	<i>llo1791</i>	<i>llb3606</i>	+	+	+	<i>vpdC</i>	Patatin domain
<i>lpg1449</i>	<i>lpp1404</i>	–	–	–	<i>lpw14671</i>	–	–	–	–	–	–	Unknown
<i>lpg1453</i>	<i>lpp1409</i>	<i>lpl1591</i>	<i>lpc0868</i>	<i>lpa2119</i>	<i>lpw14711</i>	–	–	–	–	–	–	Unknown
<i>lpg1483</i>	<i>lpp1439</i>	<i>lpl1545</i>	<i>lpc0898</i>	<i>lpa2161</i>	<i>lpw15031</i>	<i>llo1682</i>	<i>llb3727</i>	+	+	+	<i>legK1</i>	STPK
<i>lpg1484</i>	<i>lpp1440</i>	<i>lpl1544</i>	<i>lpc0899</i>	<i>lpa2162</i>	<i>lpw15041</i>	–	–	–	–	–	–	Unknown
<i>lpg1488</i>	<i>lpp1444</i>	<i>lpl1540</i>	<i>lpc0903*</i>	<i>lpa2168</i>	<i>lpw15081</i>	–	–	–	–	–	<i>lgt3/legc5</i>	Coiled-coil
<i>lpg1489</i>	<i>lpp1445</i>	<i>lpl1539</i>	<i>lpc0905</i>	<i>lpa2169</i>	<i>lpw15091</i>	–	–	–	–	–	<i>ravX</i>	Unknown
<i>lpg1491</i>	<i>lpp1447</i>	–	–	–	–	–	–	–	–	–	<i>lem9</i>	Unknown
<i>lpg1496</i>	<i>lpp1453</i>	<i>lpl1530</i>	<i>lpc0915</i>	<i>lpa2185</i>	<i>lpw15181</i>	–	–	–	–	–	<i>lem10</i>	Unknown
<i>lpg1551</i>	<i>lpp1508</i>	<i>lpl1475</i>	<i>lpc0972</i>	<i>lpa2253</i>	–	–	–	–	–	–	<i>ravY</i>	Unknown
<i>lpg1578</i>	<i>lpp4178</i>	<i>lpl4143</i>	<i>lpc1002</i>	<i>lpa2292</i>	<i>lpw16011</i>	<i>llo1503</i>	<i>llb0148</i>	+	+	+	–	Unknown
<i>lpg1588</i>	<i>lpp1546</i>	<i>lpl1437</i>	<i>lpc1013</i>	<i>lpa2305</i>	<i>lpw16131</i>	–	–	–	–	–	<i>legC6</i>	Coiled-coil
<i>lpg1598</i>	<i>lpp1556</i>	<i>lpl1427</i>	<i>lpc1025</i>	<i>lpa2317</i>	<i>lpw16231</i>	–	–	–	–	–	<i>lem11</i>	Unknown
<i>lpg1602</i>	<i>lpp1567</i>	<i>lpl1423/26*</i>	<i>lpc1028</i>	<i>lpa2318</i>	<i>lpw16241</i>	–	–	–	–	–	<i>legL2</i>	LRR
<i>lpg1621</i>	<i>lpp1591</i>	<i>lpl1402</i>	<i>lpc1048</i>	<i>lpa2346</i>	<i>lpw16461</i>	<i>llo1014</i>	<i>llb0702</i>	+	+	+	<i>ceg23</i>	Unknown
<i>lpg1625</i>	<i>lpp1595</i>	<i>lpl1398</i>	<i>lpc1052</i>	<i>lpa2350</i>	<i>lpw16511</i>	<i>llo0719</i>	<i>llb1016</i>	+	+	+	<i>lem23</i>	Unknown
<i>lpg1639</i>	<i>lpp1609</i>	<i>lpl1387</i>	<i>lpc1068</i>	<i>lpa2367</i>	<i>lpw16651</i>	–	–	–	–	–	–	Unknown
<i>lpg1642</i>	<i>lpp1612a/b</i>	<i>lpl1384</i>	<i>lpc1071</i>	<i>lpa2371</i>	<i>lpw16681</i>	–	–	–	–	–	<i>sidB</i>	Putative hydrolase
<i>lpg1654</i>	<i>lpp1625</i>	–	<i>lpc1084</i>	<i>lpa2390</i>	–	<i>llo0791</i>	<i>llb0935</i>	+	+	+	–	Unknown
<i>lpg1660</i>	<i>lpp1631</i>	<i>lpl1625</i>	<i>lpc1090</i>	<i>lpa2398</i>	<i>lpw16861</i>	–	–	–	–	–	<i>legL3</i>	LRR
<i>lpg1661</i>	<i>lpp1632</i>	<i>lpl1626</i>	<i>lpc1091</i>	<i>lpa2399</i>	<i>lpw16871</i>	<i>llo1691</i>	<i>llb3715</i>	+	+	+	–	Putative <i>N</i> -acetyl transferase
<i>lpg1666</i>	<i>lpp1637</i>	<i>lpl1631</i>	<i>lpc1096</i>	<i>lpa2408</i>	<i>lpw16921</i>	–	–	–	–	–	–	Unknown
<i>lpg1667</i>	<i>lpp1638</i>	<i>lpl1632</i>	<i>lpc1097</i>	<i>lpa2409</i>	<i>lpw16931</i>	–	–	–	–	–	–	Unknown
<i>lpg1670</i>	<i>lpp1642</i>	<i>lpl1635</i>	<i>lpc1101</i>	<i>lpa2413</i>	<i>lpw16971</i>	–	–	–	–	–	–	Unknown
<i>lpg1683</i>	–	–	<i>lpc1114</i>	<i>lpa2431</i>	–	<i>llo2508</i>	<i>llb2843</i>	+	+	+	<i>ravZ</i>	Unknown
<i>lpg1684</i>	–	–	<i>lpc1115</i>	<i>lpa2432</i>	–	<i>llo2267</i>	<i>llb3113</i>	+	+	+	–	Unknown
<i>lpg1685</i>	–	–	<i>lpc1116</i>	<i>lpa2433</i>	–	<i>llo3208</i>	<i>llb2147</i>	+	+	+	–	Unknown
<i>lpg1687</i>	<i>lpp1656</i>	<i>lpl1650</i>	<i>lpc1118</i>	<i>lpa2437</i>	<i>lpw17121</i>	–	–	–	–	–	<i>mavA</i>	Unknown
<i>lpg1689</i>	<i>lpp1658</i>	<i>lpl1652</i>	<i>lpc1120</i>	<i>lpa2439</i>	<i>lpw17141</i>	<i>llo1697</i>	<i>llb3708</i>	+	+	+	–	Unknown
<i>lpg1692</i>	–	–	<i>lpc1123</i>	<i>lpa2442</i>	–	–	–	–	–	–	–	Unknown
<i>lpg1701</i>	<i>lpp1666</i>	<i>lpl1660</i>	<i>lpc1130</i>	<i>lpa2455</i>	<i>lpw17231</i>	–	–	–	–	–	<i>ppeA/legC3</i>	Coiled-coil
<i>lpg1702</i>	<i>lpp1667</i>	<i>lpl1661</i>	<i>lpc1131</i>	<i>lpa2456</i>	<i>lpw17241</i>	–	–	–	–	–	<i>ppeB</i>	Unknown
<i>lpg1716</i>	<i>lpp1681</i>	<i>lpl1675</i>	<i>lpc1146</i>	<i>lpa2474</i>	<i>lpw17391</i>	–	–	–	–	–	–	Unknown
<i>lpg1717</i>	<i>lpp1682</i>	–	–	–	<i>lpw17401</i>	–	–	–	–	–	–	Unknown

(Continued)

Table 3 | Continued

<i>L. pneumophila</i>						<i>L. longbeachae</i>					Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b	NSW 150	D-4968	AT	98072	C-4E7		
<i>lpg1718</i>	<i>lpp1683</i>	<i>lpl1682</i>	<i>lpc1152</i>	<i>lpa2484</i>	<i>lpw17411</i>	–	–	–	–	–	<i>ankl/legAS4</i>	Ankyrin
<i>lpg1751</i>	<i>lpp1715</i>	<i>lpl1715</i>	<i>lpc1191</i>	<i>lpa2538</i>	<i>lpw17761</i>	<i>llo2314</i>	<i>llb3061</i>	+	+	+	–	Unknown
<i>lpg1752</i>	<i>lpp1716</i>	<i>lpl1716</i>	<i>lpc1192</i>	<i>lpa2539</i>	<i>lpw17771</i>	<i>llo2315</i>	<i>llb3060</i>	+	+	+	–	Unknown
<i>lpg1776</i>	<i>lpp1740</i>	<i>lpl1740</i>	<i>lpc1217</i>	<i>lpa2570</i>	<i>lpw18031</i>	<i>llo1437</i>	<i>llb0214*</i>	+	+	+	–	Unknown
<i>lpg1797</i>	–	–	<i>lpc1239</i>	<i>lpa2599</i>	<i>lpw32931</i>	–	–	–	–	–	<i>rvfA</i>	Unknown
<i>lpg1798</i>	<i>lpp1761</i>	<i>lpl1761</i>	<i>lpc1241</i>	<i>lpa2600</i>	<i>lpw18281</i>	<i>llo0991</i>	<i>llb0731</i>	+	+	+	<i>marB</i>	Unknown
<i>lpg1803</i>	<i>lpp1766</i>	<i>lpl1766</i>	<i>lpc1246</i>	<i>lpa2606</i>	<i>lpw18331</i>	<i>llo2611</i>	<i>llb2729</i>	+	+	+	–	Unknown
<i>lpg1836</i>	<i>lpp1799</i>	<i>lpl1800</i>	<i>lpc1280</i>	<i>lpa2652</i>	<i>lpw18691</i>	–	–	–	–	–	<i>ceg25</i>	Unknown
<i>lpg1851</i>	<i>lpp1818</i>	<i>lpl1817</i>	<i>lpc1296</i>	<i>lpa2675</i>	<i>lpw18871</i>	<i>llo1047</i>	<i>llb0666</i>	+	+	+	<i>lem14</i>	Unknown
<i>lpg1884</i>	<i>lpp1848</i>	<i>lpl1845</i>	<i>lpc1331</i>	<i>lpa2714</i>	<i>lpw19161</i>	–	–	–	–	–	<i>ylfB/legC2</i>	Coiled-coil
<i>lpg1888</i>	<i>lpp1855</i>	<i>lpl1850</i>	<i>lpc1336</i>	<i>lpa2723</i>	<i>lpw19211</i>	–	–	–	–	–	–	Unknown
<i>lpg1890</i>	–	<i>lpl1852</i>	<i>lpc1338</i>	<i>lpa2726</i>	<i>lpw19231</i>	–	–	–	–	–	<i>legLC8</i>	LRR, coiled-coil
<i>lpg1907</i>	<i>lpp1882</i>	<i>lpl1871</i>	<i>lpc1361</i>	<i>lpa2762</i>	<i>lpw19461</i>	<i>llo1240</i>	<i>llb0452</i>	+	+	+	–	Unknown
<i>lpg1924</i>	<i>lpp1899</i>	<i>lpl1888</i>	<i>lpc1378</i>	<i>lpa2783</i>	<i>lpw19631</i>	–	–	–	–	–	–	Unknown
<i>lpg1933</i>	<i>lpp1914</i>	<i>lpl1903</i>	<i>lpc1406</i>	<i>lpa2811</i>	<i>lpw19721</i>	–	–	–	–	–	<i>lem15</i>	Unknown
<i>lpg1947</i>	<i>lpp1930</i>	<i>lpl1917*</i>	–	<i>lpa2835</i>	<i>lpw19951</i>	–	–	–	–	–	<i>lem16</i>	Spectrin domain
<i>lpg1948</i>	–	–	–	–	–	–	–	–	–	–	<i>legLC4</i>	LRR, coiled-coil
<i>lpg1949</i>	<i>lpp1931</i>	<i>lpl1918</i>	<i>lpc1422</i>	<i>lpa2837</i>	<i>lpw19961</i>	–	–	–	–	–	<i>lem17</i>	Unknown
<i>lpg1950</i>	<i>lpp1932</i>	<i>lpl1919</i>	<i>lpc1423</i>	<i>lpa2838</i>	<i>lpw19971</i>	<i>llo1397</i>	<i>llb0259</i>	+	+	+	<i>ralF</i>	Sec7 domain
<i>lpg1953</i>	<i>lpp1935</i>	<i>lpl1922</i>	<i>lpc1426</i>	<i>lpa2842</i>	<i>lpw20041</i>	–	–	–	–	–	<i>legC4</i>	Coiled-coil
<i>lpg1958</i>	<i>lpp1940</i>	–	–	–	–	–	–	–	–	–	<i>legL5</i>	LRR
<i>lpg1959</i>	<i>lpp1941</i>	–	–	<i>lpa2857</i>	<i>lpw20101</i>	–	–	–	–	–	–	Unknown
<i>lpg1960</i>	<i>lpp1942</i>	<i>lpl1934*</i>	<i>lpc1437</i>	<i>lpa2859</i>	<i>lpw20111</i>	<i>llo0565</i>	<i>llb1288</i>	+	+	+	<i>lirA</i>	Unknown
<i>lpg1962</i>	<i>lpp1946</i>	<i>lpl1936</i>	<i>lpc1440</i>	<i>lpa2861</i>	<i>lpw20131</i>	–	–	–	–	–	<i>lirB</i>	Rotamase
<i>lpg1963</i>	–	–	<i>lpc1441/42</i>	<i>lpa2863</i>	–	–	–	–	–	–	<i>pieA/lirC</i>	Unknown
<i>lpg1964</i>	–	–	–	–	–	–	–	–	–	–	<i>pieB/lirD</i>	Unknown
<i>lpg1965</i>	–	–	<i>lpc1443/45</i>	<i>lpa2865</i>	<i>lpw20141</i>	–	–	–	–	–	<i>pieC/lirE</i>	Unknown
<i>lpg1966</i>	<i>lpp1947</i>	–	<i>lpc1446</i>	<i>lpa2867</i>	<i>lpw20151</i>	–	–	–	–	–	<i>pieD/lirF</i>	Unknown
<i>lpg1969</i>	<i>lpp1952</i>	<i>lpl1941</i>	<i>lpc1452</i>	<i>lpa2874</i>	<i>lpw20201</i>	<i>llo3131</i>	<i>llb2239</i>	+	+	+	<i>pieE</i>	Unknown
<i>lpg1972</i>	<i>lpp1955</i>	<i>lpl1950</i>	<i>lpc1459</i>	<i>lpa2884</i>	<i>lpw20291</i>	–	–	–	–	–	<i>pieF</i>	Unknown
<i>lpg1975</i>	<i>lpp1959</i>	<i>lpl1953</i>	<i>lpc1462</i>	<i>lpa2889(1)</i>	<i>lpw20351</i>	–	–	–	–	–	–	Unknown
<i>lpg1976</i>	<i>lpp1959</i>	<i>lpl1953</i>	<i>lpc1462</i>	<i>lpa2889(2)</i>	<i>lpw20351</i>	–	–	–	–	–	<i>pieG/legG1</i>	Regulator of chromosome condensation
<i>lpg1978</i>	<i>lpp1961</i>	<i>lpl1955</i>	<i>lpc1464</i>	<i>lpa2892</i>	<i>lpw20371</i>	–	–	–	–	–	<i>setA</i>	Putative Glycosyltransferase
<i>lpg1986</i>	<i>lpp1967</i>	<i>lpl1961</i>	<i>lpc1469</i>	<i>lpa2898</i>	<i>lpw20431</i>	–	–	–	–	–	–	Unknown
<i>lpg2050</i>	<i>lpp2033</i>	<i>lpl2028</i>	<i>lpc1536</i>	<i>lpa2992</i>	<i>lpw21141</i>	–	–	–	–	–	–	Unknown
<i>lpg2131</i>	–	–	–	–	–	–	–	–	–	–	<i>legA6</i>	Unknown
<i>lpg2137</i>	<i>lpp2076</i>	<i>lpl2066</i>	<i>lpc1586</i>	<i>lpa3060</i>	<i>lpw23101</i>	–	–	–	–	–	<i>legK2</i>	STPK
<i>lpg2144</i>	<i>lpp2082</i>	<i>lpl2072</i>	<i>lpc1593</i>	<i>lpa3071</i>	<i>lpw23181</i>	–	–	–	–	–	<i>ankB/legAU13/ceg27</i>	Ankyrin, F-box
<i>lpg2147</i>	<i>lpp2086</i>	<i>lpl2075</i>	<i>lpc1596</i>	<i>lpa3076</i>	<i>lpw23211</i>	–	–	–	–	–	<i>mavC</i>	Unknown
<i>lpg2148</i>	<i>lpp2087</i>	<i>lpl2076</i>	<i>lpc1597</i>	<i>lpa3077</i>	<i>lpw23221</i>	–	–	–	–	–	–	Unknown
<i>lpg2149</i>	<i>lpp2088</i>	<i>lpl2077</i>	<i>lpc1598</i>	<i>lpa3078</i>	<i>lpw23231</i>	–	–	–	–	–	–	Unknown
<i>lpg2153</i>	<i>lpp2092</i>	<i>lpl2081</i>	<i>lpc1602</i>	<i>lpa3083</i>	<i>lpw23271</i>	–	–	–	–	–	<i>sdeC</i>	Unknown
<i>lpg2154</i>	<i>lpp2093</i>	<i>lpl2082</i>	<i>lpc1603</i>	<i>lpa3086</i>	<i>lpw23281</i>	<i>llo3097</i>	<i>llb2278</i>	+	+	+	<i>sdeC</i>	Unknown
<i>lpg2155</i>	<i>lpp2094</i>	<i>lpl2083</i>	<i>lpc1604</i>	<i>lpa3087</i>	<i>lpw23291</i>	<i>llo3096</i>	<i>llb2279</i>	+	+	+	<i>sidJ</i>	Unknown
<i>lpg2156</i>	<i>lpp2095</i>	<i>lpl2084</i>	<i>lpc1605</i>	<i>lpa3088</i>	<i>lpw23301</i>	<i>llo3095</i>	<i>llb2280</i>	+	+	+	<i>sdeB</i>	Unknown
<i>lpg2157</i>	<i>lpp2096</i>	<i>lpl2085</i>	<i>lpc1618</i>	<i>lpa3037</i>	<i>lpw23331</i>	–	–	–	–	–	<i>sdeC</i>	Unknown
<i>lpg2166</i>	<i>lpp2104</i>	<i>lpl2093</i>	<i>lpc1626</i>	<i>lpa3107</i>	<i>lpw23451</i>	<i>llo2398</i>	<i>llb2969</i>	+	+	+	<i>lem19</i>	Unknown

(Continued)

Table 3 | Continued

<i>L. pneumophila</i>						<i>L. longbeachae</i>					Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b	NSW 150	D-4968	AT	98072	C-4E7		
<i>lpg2160</i>	<i>lpp2099</i>	<i>lpl2088</i>	<i>lpc1621</i>	<i>lpa3100</i>	<i>lpw23361</i>	<i>llo2645</i>	<i>llb2690</i>	+	+	+	–	Unknown
<i>lpg2176</i>	<i>lpp2128</i>	<i>lpl2102</i>	<i>lpc1635</i>	<i>lpa3118</i>	<i>lpw23561</i>	–	–	–	–	–	<i>legS2</i>	Sphingosine-1-phosphate lyase
<i>lpg2199</i>	<i>lpp2149</i>	<i>lpl2123</i>	<i>lpc1663</i>	<i>lpa3157</i>	<i>lpw23811</i>	–	–	–	–	–	<i>cegC4</i>	Unknown
<i>lpg2200</i>	<i>lpp2150</i>	<i>lpl2124</i>	<i>lpc1664</i>	<i>lpa3158</i>	<i>lpw23821</i>	–	–	–	–	–	<i>cegC4</i>	Unknown
<i>lpg2215</i>	<i>lpp2166</i>	<i>lpl2140</i>	<i>lpc1680</i>	<i>lpa3179</i>	<i>lpw24011</i>	–	–	–	–	–	<i>legA2</i>	Ankyrin
<i>lpg2216</i>	<i>lpp2167</i>	<i>lpl2141</i>	<i>lpc1681</i>	<i>lpa3180</i>	<i>lpw24021</i>	–	–	–	–	–	<i>lem20</i>	Unknown
<i>lpg2222</i>	<i>lpp2174</i>	<i>lpl2147</i>	<i>lpc1689</i>	<i>lpa3191</i>	<i>lpw24081</i>	<i>llo1443</i>	<i>llb0208</i>	+	+	+	<i>lpnE</i>	Putative beta-lactamase (SEL1 domain)
<i>lpg2223</i>	<i>lpp2175</i>	<i>lpl2149*</i>	<i>lpc1691</i>	<i>lpa3196</i>	<i>lpw24091</i>	–	–	–	–	–	–	Unknown
<i>lpg2224</i>	–	–	–	–	–	–	–	–	–	–	<i>ppgA</i>	Regulator of chromosome condensation
<i>lpg2239</i>	<i>lpp2192</i>	–	–	–	<i>lpw24261</i>	–	–	–	–	–	–	Unknown
<i>lpg2248</i>	<i>lpp2202</i>	<i>lpl2174</i>	<i>lpc1717</i>	<i>lpa3237</i>	<i>lpw24371</i>	–	–	–	–	–	<i>lem21</i>	Unknown
<i>lpg2271</i>	<i>lpp2225</i>	<i>lpl2197</i>	<i>lpc1740</i>	<i>lpa3268</i>	<i>lpw24611</i>	<i>llo2530</i>	<i>llb2821</i>	+	+	+	–	Unknown
<i>lpg2298</i>	<i>lpp2246</i>	<i>lpl2217</i>	<i>lpc1763</i>	<i>lpa3296</i>	<i>lpw24841</i>	<i>llo1707</i>	<i>llb3696</i>	+	+	+	<i>yIfA/legC7</i>	Coiled-coil
<i>lpg2300</i>	<i>lpp2248</i>	<i>lpl2219</i>	<i>lpc1765</i>	<i>lpa3298</i>	<i>lpw24871</i>	<i>llo0584</i>	<i>llb1266</i>	+	+	+	<i>ankH/legA3, ankW</i>	Ankyrin, Nf-kappaB inhibitor
<i>lpg2311</i>	<i>lpp2259</i>	<i>lpl2230</i>	<i>lpc1776</i>	<i>lpa3312</i>	<i>lpw24981</i>	–	–	–	–	–	<i>ceg28</i>	Unknown
<i>lpg2322</i>	<i>lpp2270</i>	<i>lpl2242</i>	<i>lpc1789</i>	<i>lpa3328</i>	<i>lpw25121</i>	<i>llo0570</i>	<i>llb1282</i>	+	+	+	<i>ankK/legA5</i>	Ankyrin
<i>lpg2327</i>	<i>lpp2275</i>	<i>lpl2247</i>	<i>lpc1794</i>	<i>lpa3335</i>	<i>lpw25181</i>	–	–	–	–	–	–	Unknown
<i>lpg2328</i>	<i>lpp2276</i>	<i>lpl2248</i>	<i>lpc1795</i>	<i>lpa3336</i>	<i>lpw25191</i>	–	–	–	–	–	<i>lem22</i>	Unknown
<i>lpg2344</i>	<i>lpp2292</i>	<i>lpl2265</i>	<i>lpc1812</i>	<i>lpa3355</i>	<i>lpw25371</i>	–	–	–	–	–	<i>mavE</i>	Unknown
<i>lpg2351</i>	<i>lpp2300</i>	<i>lpl2273</i>	<i>lpc1820</i>	<i>lpa3367</i>	<i>lpw25461</i>	<i>llo2850</i>	<i>llb2466</i>	+	+	+	<i>mavF</i>	Unknown
<i>lpg2359</i>	<i>lpp2308</i>	<i>lpl2281</i>	<i>lpc1828</i>	<i>lpa3376</i>	<i>lpw25561</i>	<i>llo2856</i>	<i>llb2460</i>	+	+	+	–	Unknown
<i>lpg2370</i>	–	–	–	–	–	–	–	–	–	–	–	HipA fragment
<i>lpg2372</i>	<i>lpp3009</i>	–	<i>lpc3248</i>	<i>lpa4300</i>	–	–	–	–	–	–	–	Unknown
<i>lpg2382</i>	<i>lpp2444</i>	<i>lpl2300</i>	<i>lpc2108</i>	<i>lpa3446</i>	<i>lpw25841</i>	<i>llo1576</i>	<i>llb0071</i>	+	+	+	–	Unknown
<i>lpg2391</i>	<i>lpp2458</i>	<i>lpl2315</i>	<i>lpc2086</i>	<i>lpa3485</i>	<i>lpw26021</i>	–	–	–	–	–	<i>sdbC</i>	Unknown
<i>lpg2392</i>	<i>lpp2459</i>	<i>lpl2316</i>	<i>lpc2085</i>	<i>lpa3486</i>	<i>lpw26041</i>	–	–	–	–	–	<i>legL6</i>	LRR
<i>lpg2400</i>	–	<i>lpl2323</i>	–	–	<i>lpw26121</i>	–	–	–	–	–	<i>legL6</i>	LRR
<i>lpg2406</i>	<i>lpp2472</i>	<i>lpl2329</i>	<i>lpc2070</i>	<i>lpa3506</i>	<i>lpw26191</i>	<i>llo2172</i>	<i>llb3225</i>	+	+	+	<i>lem23</i>	Unknown
<i>lpg2407</i>	<i>lpp2474</i>	–	<i>lpc2069</i>	<i>lpa3507</i>	–	–	–	–	–	–	–	Unknown
<i>lpg2409</i>	<i>lpp2476</i>	<i>lpl2332</i>	<i>lpc2067</i>	<i>lpa3511</i>	<i>lpw26241</i>	–	–	–	–	–	<i>ceg29</i>	Unknown
<i>lpg2410</i>	<i>lpp2479</i>	<i>lpl2334</i>	<i>lpc2065</i>	<i>lpa3513</i>	<i>lpw26261</i>	–	–	–	–	–	<i>vpdA</i>	Patatin domain
<i>lpg2411</i>	<i>lpp2480</i>	<i>lpl2335</i>	<i>lpc2064</i>	<i>lpa3515</i>	<i>lpw26281</i>	<i>llo2227</i>	<i>llb3158</i>	+	+	+	<i>lem24</i>	Unknown
–	<i>lpp2486</i>	–	–	–	–	–	–	–	–	–	–	F-box
<i>lpg2416</i>	–	<i>lpl2339</i>	<i>lpc2057</i>	<i>lpa3527</i>	<i>lpw26351</i>	–	–	–	–	–	<i>legA1</i>	Unknown
<i>lpg2420</i>	–	<i>lpl2343</i>	<i>lpc2056</i>	<i>lpa3529</i>	<i>lpw26391</i>	–	–	–	–	–	–	Unknown
<i>lpg2422</i>	<i>lpp2487</i>	<i>lpl2345</i>	<i>lpc2055</i>	<i>lpa3530</i>	<i>lpw26401</i>	<i>llo1650</i>	<i>llb3763/6</i>	+	+	+	<i>lem25</i>	Unknown
<i>lpg2424</i>	<i>lpp2489</i>	<i>lpl2347</i>	<i>lpc2053</i>	<i>lpa3532</i>	<i>lpw26421</i>	–	–	–	–	–	<i>mavG</i>	Unknown
<i>lpg2425</i>	<i>lpp2491</i>	<i>lpl2348</i>	<i>lpc2051</i>	<i>lpa3537</i>	<i>lpw26431</i>	–	–	–	–	–	<i>mavH</i>	Unknown
<i>lpg2433</i>	<i>lpp2500</i>	<i>lpl2353</i>	<i>lpc2043</i>	<i>lpa3548</i>	<i>lpw26521</i>	–	–	–	–	–	<i>ceg30</i>	Unknown
<i>lpg2434</i>	<i>lpp2501</i>	<i>lpl2355</i>	<i>lpc2042</i>	<i>lpa3550</i>	<i>lpw26531</i>	–	–	–	–	–	–	Unknown
<i>lpg2443</i>	<i>lpp2510</i>	<i>lpl2363</i>	<i>lpc2033</i>	<i>lpa3562</i>	–	–	–	–	–	–	–	Unknown
<i>lpg2444</i>	<i>lpp2511</i>	<i>lpl2364</i>	<i>lpc2032</i>	<i>lpa3563</i>	<i>lpw26641</i>	–	–	–	–	–	<i>mavI</i>	Unknown

(Continued)

Table 3 | Continued

<i>L. pneumophila</i>						<i>L. longbeachae</i>					Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b	NSW 150	D-4968	AT	98072	C-4E7		
<i>lpg2452</i>	<i>lpp2517</i>	<i>lpl2370</i>	<i>lpc2026</i>	<i>lpa3574</i>	<i>lpw26701</i>	–	–	–	–	–	<i>ankF/legA14/ceg31</i>	Ankyrin
<i>lpg2456</i>	<i>lpp2522</i>	<i>lpl2375</i>	<i>lpc2020</i>	<i>lpa3583</i>	<i>lpw26751</i>	<i>llo0365</i>	<i>llb1493</i>	+	+	+	<i>ankD/legA15</i>	Ankyrin
<i>lpg2461</i>	<i>lpp2527</i>	<i>lpl2380</i>	<i>lpc2015</i>	<i>lpa3589</i>	<i>lpw26801</i>	<i>llo1991</i>	<i>llb3433</i>	+	+	+	–	Unknown
<i>lpg2464</i>	–	<i>lpl2384</i>	–	–	<i>lpw26851</i>	–	–	–	–	–	<i>sidM/drrA</i>	Unknown
<i>lpg2465</i>	–	<i>lpl2385</i>	–	–	<i>lpw26861</i>	–	–	–	–	–	<i>sidD</i>	Unknown
<i>lpg2490</i>	<i>lpp2555</i>	<i>lpl2411</i>	<i>lpc1987</i>	<i>lpa3628</i>	<i>lpw27131</i>	–	–	–	–	–	<i>lepB</i>	Coiled-coil, Rab1 GAP
<i>lpg2482</i>	<i>lpp2546</i>	<i>lpl2402</i>	<i>lpc1996</i>	<i>lpa3615</i>	<i>lpw27041</i>	–	–	–	–	–	<i>sdbB</i>	Unknown
<i>lpg2498</i>	<i>lpp2566</i>	<i>lpl2420</i>	<i>lpc1975</i>	<i>lpa3646</i>	<i>lpw27241</i>	–	–	–	–	–	<i>mavJ</i>	Unknown
<i>lpg2504</i>	<i>lpp2572</i>	<i>lpl2426</i>	<i>lpc1967</i>	<i>lpa3658</i>	<i>lpw27301</i>	<i>llo2525</i>	<i>llb2826</i>	+	+	+	<i>sidI/ceg32</i>	Unknown
<i>lpg2505</i>	<i>lpp2573</i>	<i>lpl2427</i>	<i>lpc1966</i>	<i>lpa3659</i>	<i>lpw27311</i>	<i>llo2526</i>	<i>llb2825</i>	+	+	+	–	Unknown
<i>lpg2508</i>	<i>lpp2576</i>	<i>lpl2430</i>	<i>lpc1962/63*</i>	<i>lpa3666</i>	<i>lpw27341</i>	–	–	–	–	–	<i>sdjA</i>	Unknown
<i>lpg2509</i>	<i>lpp2577</i>	<i>lpl2431</i>	<i>lpc1961</i>	<i>lpa3667</i>	<i>lpw27351</i>	<i>llo3097</i>	<i>llb2278</i>	+	+	+	<i>sdeD</i>	Unknown
<i>lpg2510</i>	<i>lpp2578</i>	<i>lpl2432</i>	<i>lpc1960</i>	<i>lpa3668</i>	–	<i>llo3098</i>	<i>llb2276</i>	+	+	+	<i>sdcA</i>	Unknown
<i>lpg2511</i>	<i>lpp2579</i>	<i>lpl2433</i>	<i>lpc1959</i>	<i>lpa3669</i>	<i>lpw27371</i>	–	–	–	–	–	<i>sidC</i>	PI(4)P binding domain
<i>lpg2523</i>	–	–	–	–	<i>lpw27501</i>	–	–	–	–	–	<i>lem26</i>	Unknown
<i>lpg2525</i>	–	–	–	–	–	–	–	–	–	–	<i>mavK</i>	Unknown
<i>lpg2526</i>	<i>lpp2591</i>	<i>lpl2446</i>	<i>lpc1946</i>	<i>lpa3687</i>	<i>lpw27521</i>	–	–	–	–	–	<i>mavL</i>	Unknown
<i>lpg2527</i>	<i>lpp2592</i>	<i>lpl2447</i>	<i>lpc1944</i>	<i>lpa3688</i>	<i>lpw27531</i>	<i>llo3335</i>	<i>llb2002</i>	+	+	+	–	Unknown
<i>lpg2529</i>	<i>lpp2594</i>	<i>lpl2449</i>	<i>lpc1942</i>	<i>lpa3692</i>	<i>lpw27551</i>	<i>llo2238</i>	<i>llb3146</i>	+	+	+	<i>lem27</i>	Unknown
<i>lpg2538</i>	<i>lpp2604</i>	<i>lpl2459</i>	<i>lpc1930</i>	<i>lpa3706</i>	<i>lpw27671</i>	–	–	–	–	–	–	Unknown
<i>lpg2539</i>	<i>lpp2605</i>	<i>lpl2460</i>	<i>lpc1929</i>	<i>lpa3707</i>	<i>lpw27681</i>	<i>llo1348</i>	<i>llb0317</i>	+	+	+	–	Unknown
<i>lpg2541</i>	<i>lpp2607</i>	<i>lpl2462</i>	<i>lpc1927</i>	<i>lpa3710</i>	<i>lpw27701</i>	–	–	–	–	–	–	Unknown
<i>lpg2546</i>	<i>lpp2615</i>	–	<i>lpc1919</i>	<i>lpa3727</i>	<i>lpw27791</i>	–	–	–	–	–	–	Unknown
<i>lpg2552</i>	<i>lpp2622</i>	<i>lpl2473</i>	<i>lpc1911</i>	<i>lpa3738</i>	<i>lpw27871</i>	<i>llo1062</i>	<i>llb0648</i>	+	+	+	–	Unknown
<i>lpg2555</i>	<i>lpp2625</i>	<i>lpl2480</i>	<i>lpc1908</i>	<i>lpa3743</i>	<i>lpw27901</i>	<i>llo2220</i>	<i>llb3170</i>	+	+	+	–	Unknown
<i>lpg2556</i>	<i>lpp2626</i>	<i>lpl2481</i>	<i>lpc1906</i>	<i>lpa3745</i>	<i>lpw27911</i>	<i>llo2218</i>	<i>llb3172</i>	+	+	+	<i>legK3</i>	STPK
<i>lpg2577</i>	<i>lpp2629</i>	<i>lpl2499</i>	<i>lpc0570</i>	<i>lpa3768</i>	<i>lpw28241</i>	–	–	–	–	–	<i>mavM</i>	Unknown
<i>lpg2584</i>	<i>lpp2637</i>	<i>lpl2507</i>	<i>lpc0561</i>	<i>lpa3779</i>	<i>lpw28321</i>	–	–	–	–	–	<i>sidF</i>	Unknown
<i>lpg2588</i>	<i>lpp2641</i>	<i>lpl2511</i>	<i>lpc0557</i>	<i>lpa3784</i>	<i>lpw28361</i>	<i>llo2622</i>	<i>llb2718</i>	+	+	+	<i>legS1</i>	Unknown
<i>lpg2591</i>	<i>lpp2644</i>	<i>lpl2514</i>	<i>lpc0551</i>	<i>lpa3790</i>	<i>lpw28391</i>	<i>llo0626</i>	<i>llb1219</i>	+	+	+	<i>ceg33</i>	Unknown
<i>lpg2603</i>	<i>lpp2656</i>	<i>lpl2526</i>	<i>lpc0539</i>	<i>lpa3807</i>	<i>lpw28521</i>	–	–	–	–	–	<i>lem28</i>	Unknown
<i>lpg2628</i>	<i>lpp2681</i>	<i>lpl2553</i>	<i>lpc0513</i>	<i>lpa3846</i>	<i>lpw28781</i>	–	–	–	–	–	–	Unknown
<i>lpg2637</i>	<i>lpp2690</i>	<i>lpl2562</i>	<i>lpc0503</i>	<i>lpa3859</i>	<i>lpw28871</i>	–	–	–	–	–	–	Unknown
<i>lpg2638</i>	<i>lpp2691</i>	<i>lpl2563</i>	<i>lpc0502</i>	<i>lpa3861</i>	<i>lpw28891</i>	<i>llo2645</i>	<i>llb2690</i>	+	+	+	<i>mavV</i>	Unknown
<i>lpg2692</i>	<i>lpp2746</i>	<i>lpl2619</i>	<i>lpc0444</i>	<i>lpa3929</i>	<i>lpw29461</i>	–	–	–	–	–	–	Unknown
<i>lpg2694</i>	<i>lpp2748</i>	<i>lpl2621</i>	<i>lpc0442</i>	<i>lpa3931</i>	<i>lpw29481</i>	–	–	–	–	–	<i>legD1</i>	Phyhd1 protein
<i>lpg2718</i>	<i>lpp2775</i>	<i>lpl2646</i>	<i>lpc0415</i>	<i>lpa3966</i>	<i>lpw29771</i>	–	–	–	–	–	<i>wipA</i>	Unknown
<i>lpg2720</i>	<i>lpp2777</i>	<i>lpl2648</i>	<i>lpc0413</i>	<i>lpa3968</i>	<i>lpw29791</i>	–	–	–	–	–	<i>legN</i>	cAMP-binding protein
<i>lpg2744</i>	<i>lpp2800</i>	<i>lpl2669</i>	<i>lpc0386</i>	<i>lpa4004</i>	<i>lpw30031</i>	–	–	–	–	–	–	Unknown
<i>lpg2745</i>	<i>lpp2801</i>	<i>lpl2670</i>	<i>lpc0385</i>	<i>lpa4005</i>	<i>lpw30041</i>	<i>llo0308</i>	<i>llb1553</i>	+	+	+	–	Unknown
<i>lpg2793</i>	<i>lpp2839</i>	<i>lpl2708</i>	<i>lpc3079</i>	<i>lpa4063</i>	<i>lpw30471</i>	–	–	–	–	–	<i>lepA</i>	Effector protein A
<i>lpg2804</i>	<i>lpp2850</i>	<i>lpl2719</i>	<i>lpc3090</i>	<i>lpa4076</i>	<i>lpw30591</i>	<i>llo0267</i>	<i>llb1598</i>	+	+	+	<i>lem29</i>	Unknown
<i>lpg2815</i>	<i>lpp2867</i>	<i>lpl2730</i>	<i>lpc3101</i>	<i>lpa4089</i>	<i>lpw30711</i>	<i>llo0254</i>	<i>llb1612</i>	+	+	+	<i>mavN</i>	Unknown
<i>lpg2826</i>	–	<i>lpl2741</i>	<i>lpc3113</i>	<i>lpa4104</i>	<i>lpw30831</i>	–	–	–	–	–	<i>ceg34</i>	Unknown
<i>lpg2828</i>	<i>lpp2882</i>	<i>lpl2743</i>	<i>lpc3115</i>	<i>lpa4109</i>	<i>lpw30851</i>	<i>llo0783</i>	<i>llb0944</i>	+	+	+	–	Unknown
<i>lpg2829</i>	<i>lpp2883/86*</i>	–	–	–	<i>lpw30861</i>	–	–	–	–	–	<i>sidH</i>	Unknown
<i>lpg2830</i>	<i>lpp2887</i>	–	–	–	<i>lpw30881</i>	–	–	–	–	–	<i>lubX/legU2</i>	U-box motif
<i>lpg2831</i>	<i>lpp2888</i>	–	–	–	<i>lpw30891</i>	–	–	–	–	–	<i>VipD</i>	Patatin-like phospholipase

(Continued)

Table 3 | Continued

<i>L. pneumophila</i>						<i>L. longbeachae</i>					Name	Product
Phila	Paris	Lens	Corby	Alcoy	130b	NSW 150	D-4968	AT	98072	C-4E7		
<i>lpg2832</i>	<i>lpp2889</i>	<i>lpl2744</i>	<i>lpc3116</i>	<i>lpa4110</i>	<i>lpw30921</i>	<i>llo0214</i>	<i>llb1656</i>	+	+	+	–	Putative hydrolase
<i>lpg2844</i>	<i>lpp2903</i>	<i>lpl2756</i>	<i>lpc3128</i>	<i>lpa4133</i>	–	–	–	–	–	–	–	Unknown
<i>lpg2862</i>	–	–	–	–	–	–	–	–	–	–	<i>Lgt2/legC8</i>	Coiled-coil
<i>lpg2874</i>	<i>lpp2933</i>	<i>lpl2787</i>	<i>lpc3160</i>	<i>lpa4176</i>	<i>lpw31411</i>	–	–	–	–	–	–	Unknown
<i>lpg2879</i>	<i>lpp2938</i>	<i>lpl2792</i>	<i>lpc3165</i>	<i>lpa4186</i>	<i>lpw31471</i>	<i>llo0192</i>	<i>llb1681</i>	+	+	+	–	Unknown
<i>lpg2884</i>	<i>lpp2943</i>	<i>lpl2797</i>	<i>lpc3170</i>	<i>lpa4193</i>	<i>lpw31531</i>	<i>llo0197</i>	<i>llb1676</i>	+	+	+	–	Unknown
<i>lpg2885</i>	<i>lpp2944</i>	<i>lpl2798</i>	<i>lpc3171</i>	–	<i>lpw31541</i>	–	–	–	–	–	–	Unknown
<i>lpg2888</i>	<i>lpp2947</i>	<i>lpl2801</i>	<i>lpc3174</i>	<i>lpa4199</i>	<i>lpw31571</i>	<i>llo0200</i>	<i>llb1672</i>	+	+	+	–	Unknown
<i>lpg2912</i>	<i>lpp2980</i>	<i>lpl2830</i>	<i>lpc3214</i>	<i>lpa4255</i>	<i>lpw31931</i>	–	–	–	–	–	–	Unknown
<i>lpg2936</i>	<i>lpp3004</i>	<i>lpl2865</i>	<i>lpc3243</i>	<i>lpa4293</i>	<i>lpw32251</i>	<i>llo0081</i>	<i>llb1804</i>	+	+	+	–	rRNA small subunit methyltransferase E
<i>lpg2975</i>	<i>lpp3047</i>	<i>lpl2904</i>	<i>lpc3290</i>	<i>lpa4358</i>	–?	<i>llo3405</i>	<i>llb1930</i>	+	+	+	–	Unknown
<i>lpg2999</i>	<i>lpp3071</i>	<i>lpl2927</i>	<i>lpc3315</i>	<i>lpa4395</i>	<i>lpw32851</i>	–	–	–	–	–	<i>legP</i>	Astacin protease
<i>lpg3000</i>	<i>lpp3072</i>	<i>lpl2928</i>	<i>lpc3316</i>	<i>lpa4397</i>	<i>lpw32861</i>	<i>llo3444</i>	<i>llb1887</i>	+	+	+	–	Unknown

List of substrates is based on Isberg et al. (2009), De Felipe et al. (2008), Ninio et al. (2009), Zhu et al. (2011); AT=ATCC33462; *pseudogene, +? or –? strains 130b, C-4E7 and 98072 are not a finished sequence and not manually curated. Thus absence of a substrate can also be due to gaps in the sequence; shaded in gray, substrates conserved in all *L. pneumophila* and *L. longbeachae* genomes.

sphingosine-1-phosphate lyase and sphingosine kinase, eukaryotic like glycoamylase, cytokinin oxidase, zinc metalloprotease, or an RNA binding precursor (Cazalet et al., 2004; De Felipe et al., 2005; Bruggemann et al., 2006). Function prediction based on similarity searches suggested that many of these proteins are implicated in modulating host cell functions to the pathogens advantage (Cazalet et al., 2004). Recent functional studies confirm these predictions.

As a first example, it was shown that *L. pneumophila* is able to interfere with the host ubiquitination pathway. The *L. pneumophila* U-box containing protein LubX was shown to be a secreted effector of the Dot/Icm secretion system that mediates polyubiquitination of a host kinase Clk1 (Kubori et al., 2008). Recently, LubX was described as the first example of an effector protein, which targets and regulates another effector within host cells, as it functions as an E3 ubiquitin ligase that hijacks the host proteasome to specifically target the bacterial effector protein SidH for degradation. Delayed delivery of LubX to the host cytoplasm leads to the shutdown of SidH within the host cells at later stages of infection. This demonstrates a sophisticated level of co-evolution between eukaryotic cells and *L. pneumophila* involving an effector that functions as a key regulator to temporally coordinate the function of a cognate effector protein (Kubori et al., 2010; Luo, 2011). Furthermore, AnkB/Lpp2028, one of the three F-box proteins of *L. pneumophila*, was shown to be a T4SS effector that is implicated in virulence of *L. pneumophila* and in recruiting ubiquitinated proteins to the LCV (Al-Khodori et al., 2008; Price et al., 2009; Habyarimana et al., 2010; Lomma et al., 2010).

A second example is the apyrases (Lpg1905 and Lpg0971) encoded in the *L. pneumophila* genomes. Indeed, both are secreted enzymes important for intracellular replication of *L. pneumophila*. Lpg1905 is a novel prokaryotic ecto-NTPDase, similar to CD39/NTPDase1, which is characterized by the presence of

five apyrase-conserved regions and enhances the replication of *L. pneumophila* in eukaryotic cells (Sansom et al., 2007). Apart from ATP and ADP, Lpg1905 also cleaves GTP and GDP with similar efficiency to ATP and ADP, respectively (Sansom et al., 2008). A third example is a *L. pneumophila* homolog of the highly conserved eukaryotic enzyme sphingosine-1-phosphate lyase (SPL). In eukaryotes, SPL is an enzyme that catalyzes the irreversible cleavage of sphingosine-1-phosphate (S1P). S1P is implicated in various physiological processes like cell survival, apoptosis, proliferation, migration, differentiation, platelet aggregation, angiogenesis, lymphocyte trafficking and development. Despite the fact that the function of the *L. pneumophila* Spl remains actually unknown, the hypothesis is that it plays a role in autophagy and/or apoptosis (Cazalet et al., 2004; Bruggemann et al., 2006). Recently it has been shown that the *L. pneumophila* Spl is a secreted effector of the Dot/Icm T4SS, that it is able to complement the sphingosine-sensitive phenotype of *Saccharomyces cerevisiae*. Moreover, *L. pneumophila* Spl co-localizes to the host cell mitochondria (Degtyar et al., 2009).

Taken together, the many different functional studies undertaken based on the results of the genome sequence analyses deciphering the roles of the eukaryotic like proteins have clearly established that they are secreted virulence factors that are involved in host cell adhesion, formation of the LCV, modulation of host cell functions, induction of apoptosis and egress of *Legionella* (Nora et al., 2009; Hubber and Roy, 2010). Most of these effector proteins are expressed at different stages of the intracellular life cycle of *L. pneumophila* (Bruggemann et al., 2006) and are delivered to the host cell by the Dot/Icm T4SS. Thus molecular mimicry of eukaryotic proteins is a major virulence strategy of *L. pneumophila*.

As expected, eukaryotic like proteins and proteins encoding domains mainly found in eukaryotic proteins are also present in the *L. longbeachae* genomes. However, between the two species a

considerable diversity in the repertoire of these proteins exists. For example Spl, LubX, the three *L. pneumophila* F-box proteins, and the homolog of one (Lpg1905) of the two apyrases are missing in all sequenced *L. longbeachae* genomes. In contrast a glycoamylase (Herrmann et al., 2011) and an uridine kinase homolog are present also in *L. longbeachae* (Cazalet et al., 2010; Kozak et al., 2010; Table 3). However, other proteins encoded by the *L. longbeachae* genome contain U-box and F-box domains and might therefore fulfill similar functions. Thus, although the specific proteins may not be conserved, the eukaryotic like protein–protein interaction domains found in *L. pneumophila* are also present in *L. longbeachae*.

The differences in trafficking between *L. longbeachae* and *L. pneumophila* mentioned above might be related to specific effectors encoded by *L. longbeachae*. A search for such specific putative effectors of *L. longbeachae* identified several proteins that might contribute to these differences like a family of Ras-related small GTPases (Cazalet et al., 2010; Kozak et al., 2010). These proteins may be involved in vesicular trafficking and thus may account at least partly for the specificities of the *L. longbeachae* life cycle. *L. pneumophila* is also known to exploit monophosphorylated host phosphoinositides (PI) to anchor the effector proteins SidC, SidM/DrrA, LpnE, and LidA to the membrane of the replication vacuole (Machner and Isberg, 2006; Murata et al., 2006; Weber et al., 2006, 2009; Newton et al., 2007; Brombacher et al., 2009). *L. longbeachae* may employ an additional strategy to interfere with the host PI as a homolog of the mammalian PI metabolizing enzyme phosphatidylinositol-4-phosphate 5-kinase was identified in its genome. One could speculate that this protein allows direct modulation of the host cell PI levels.

Interestingly, although 23 of the 29 ankyrin proteins identified in the *L. pneumophila* strains are absent from the *L. longbeachae* genome, *L. longbeachae* encodes a total of 23 specific ankyrin repeat proteins (Table 3). For example, *L. pneumophila* AnkX/AnkN that was shown to interfere with microtubule-dependent vesicular transport is missing in *L. longbeachae* (Pan et al., 2008). However, *L. longbeachae* encodes a putative tubulin-tyrosine ligase (TTL). TTL catalyzes the ATP-dependent post-translational addition of a tyrosine to the carboxy terminal end of deetyrosinated alpha-tubulin. Although the exact physiological function of alpha-tubulin has so far not been established, it has been linked to altered microtubule structure and function (Eisner et al., 1999). Thus this protein might take over this function in *L. longbeachae*.

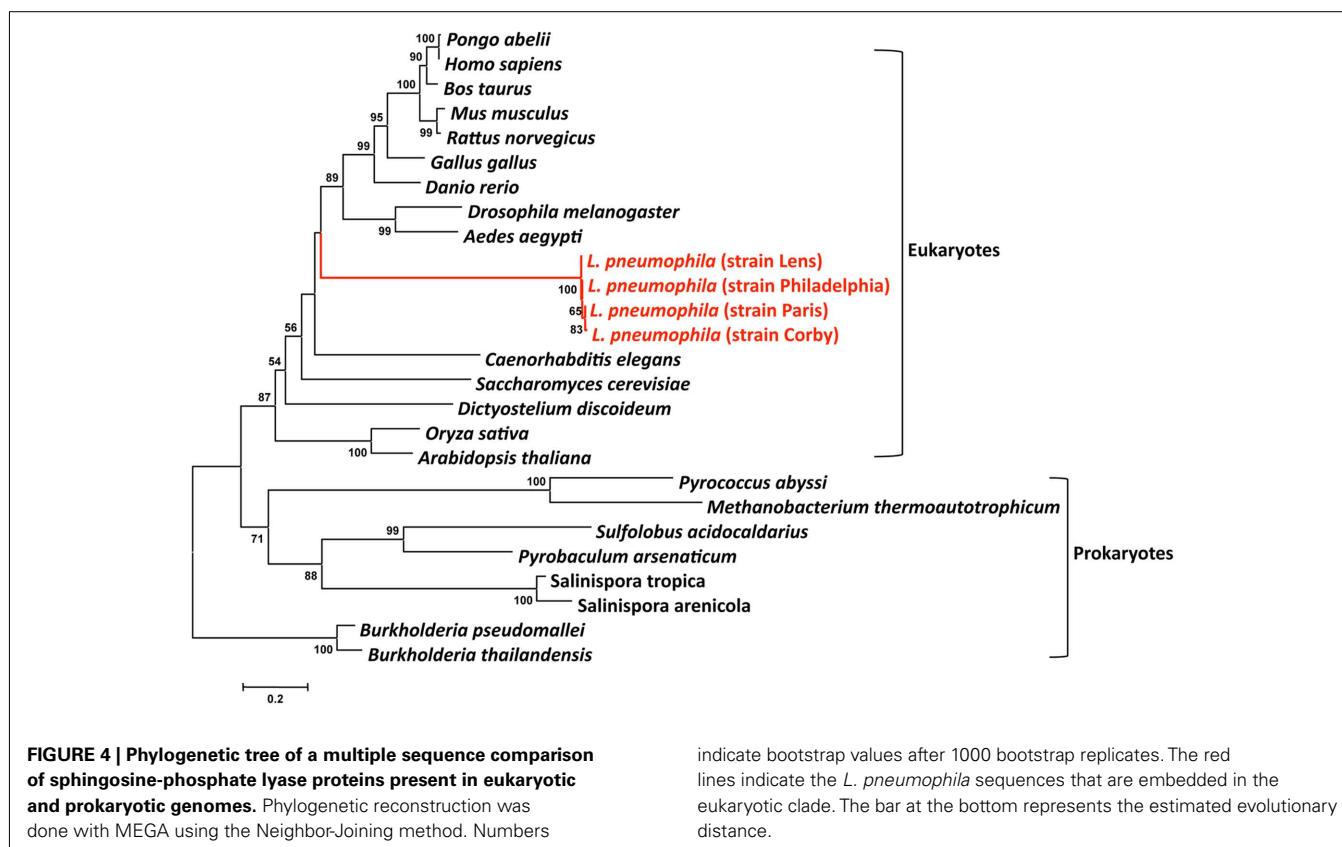
Legionella longbeachae is the first bacterial genome encoding a protein containing an Src Homology 2 (SH2) domain. SH2 domains, in eukaryotes, have regulatory functions in various intracellular signaling cascades. Furthermore, *L. longbeachae* encodes two proteins with pentatricopeptide repeat (PPR) domains. This family seems to be greatly expanded in plants, where they appear to play essential roles in organellar RNA metabolism (Lurin et al., 2004; Nakamura et al., 2004; Schmitz-Linneweber and Small, 2008). Only 12 bacterial PPR domain proteins have been identified to date, all encoded by two species, the plant pathogens *Ralstonia solanacearum* and the facultative photosynthetic bacterium *Rhodobacter sphaeroides*. Thus, genome analysis revealed a particular feature of the *Legionella* genomes, the presence of

many eukaryotic like proteins and protein domains, some of which are common to the two *Legionella* species, others which are specific and may thus account for the species specific features in intracellular trafficking and niche adaptation in the environment.

SURFACE STRUCTURES – A CLUE TO MOUSE SUSCEPTIBILITY TO INFECTION WITH LEGIONELLA

Despite the presence of many different species of *Legionella* in aquatic reservoirs, the vast majority of human disease is caused by a single serogroup (Sg) of a single species, namely *L. pneumophila* Sg1, which is responsible for about 84% of all cases worldwide (Yu et al., 2002). Similar results are obtained for *L. longbeachae*. Two serogroups are described, but *L. longbeachae* Sg1 is predominant in human disease. Lipopolysaccharide (LPS) is the basis for the classification of serogroups but it is also a major immunodominant antigen of *L. pneumophila* and *L. longbeachae*. Interestingly, it has also been shown that membrane vesicles shed by virulent *L. pneumophila* containing LPS are sufficient to inhibit phagosome–lysosome fusion (Fernandez-Moreira et al., 2006). Results obtained from large-scale genome comparisons of *L. pneumophila* suggested that LPS of Sg1 itself might be implicated in the predominance of Sg1 strains in human disease compared to other serogroups of *L. pneumophila* and other *Legionella* species (Cazalet et al., 2008). A comparative search for LPS coding regions in the genome of *L. longbeachae* NSW 150 identified two gene clusters encoding proteins that could be involved in production of lipopolysaccharide (LPS) and/or capsule. Neither shared homology with the *L. pneumophila* LPS biosynthesis gene cluster suggesting considerable differences in this major immunodominant antigen between the two *Legionella* species. However, homologs of *L. pneumophila* lipidA biosynthesis genes (LpxA, LpxB, LpxD, and WaaM) are present. Electron microscopy also demonstrated that, in contrast to *L. pneumophila*, *L. longbeachae* produces a capsule-like structure, suggesting that one of the aforementioned gene cluster encodes LPS and the other the capsule (Cazalet et al., 2010).

As mentioned in the introduction, only A/J mice are permissive for replication of *L. pneumophila*, in contrast A/J, C57BL/6, and BALB/c mice are all permissive for replication of *L. longbeachae*. In C57BL/6 mice cytosolic flagellin of *L. pneumophila* triggers Naip5-dependent caspase-1 activation and subsequent proinflammatory cell death by pyroptosis rendering them resistant to infection (Diez et al., 2003; Wright et al., 2003; Molofsky et al., 2006; Ren et al., 2006; Zamboni et al., 2006; Lamkanfi et al., 2007; Lightfield et al., 2008). Genome analysis shed light on the reasons for these differences. *L. longbeachae* does not carry any flagellar biosynthesis genes except the sigma factor FliA, the regulator FleN, the two-component system FleR/FleS and the flagellar basal body rod modification protein FlgD (Cazalet et al., 2010; Kozak et al., 2010). Analysis of the genome sequences of strains *L. longbeachae* D-4968, ATCC33642, 98072, and C-4E7 as well as a PCR-based screening of 50 *L. longbeachae* isolates belonging to both serogroups by Kozak et al. (2010) and of 15 additional isolates by Cazalet et al. (2010) did not detect flagellar genes in any isolate confirming that *L. longbeachae*, in contrast to *L. pneumophila* does not synthesize flagella. Interestingly, all genes bordering flagellar gene clusters are conserved between *L. longbeachae* and *L. pneumophila*, suggesting deletion of these regions from the *L. longbeachae* genome. This



result suggests, that *L. longbeachae* fails to activate caspase-1 due to the lack of flagellin, which may also partly explain the differences in mouse susceptibility to *L. pneumophila* and *L. longbeachae* infection. The putative *L. longbeachae* capsule may also contribute to this difference.

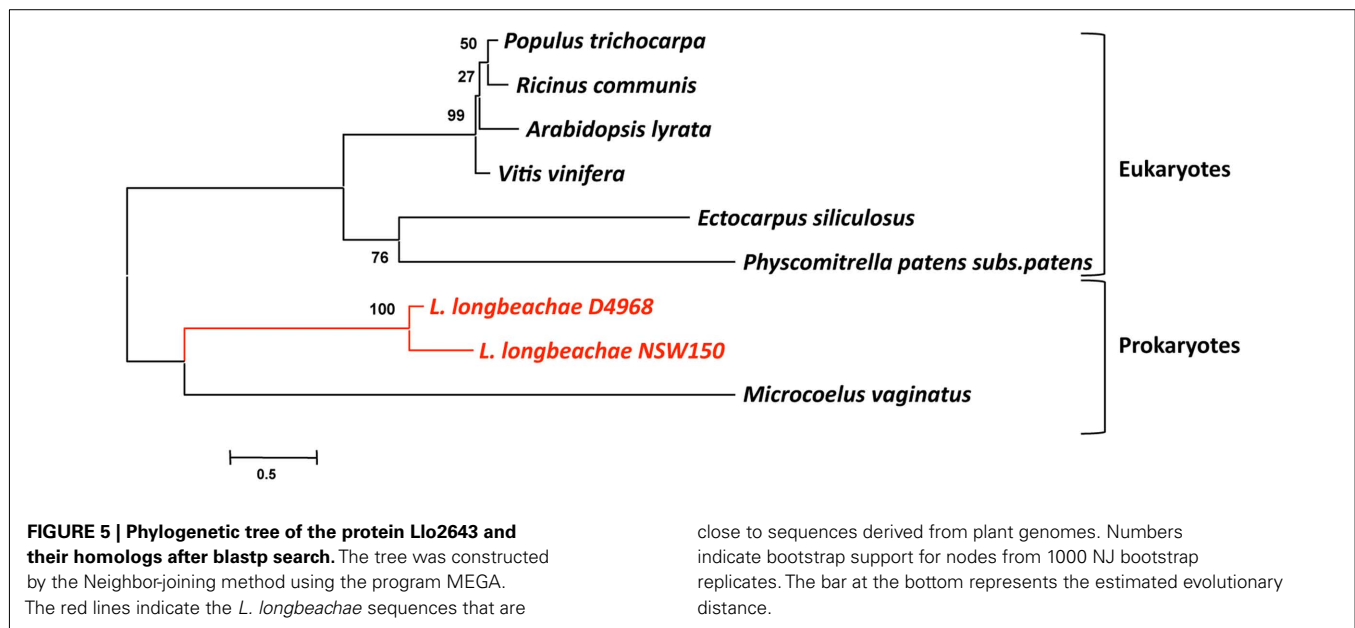
Quite interestingly, although *L. longbeachae* does not encode flagella, it encodes a putative chemotaxis system. Chemotaxis enables bacteria to find favorable conditions by migrating toward higher concentrations of attractants. In many bacteria, the chemotactic response is mediated by a two-component signal transduction pathway, comprising a histidine kinase CheA and a response regulator CheY. Homologs of this regulatory system are present in the *L. longbeachae* genomes sequenced (Cazalet et al., 2010; Kozak et al., 2010). Furthermore, two homologs of the “adaptor” protein CheW that associate with CheA or cytoplasmic chemosensory receptors are present. Ligand-binding to receptors regulates the autophosphorylation activity of CheA in these complexes. The CheA phosphoryl group is subsequently transferred to CheY, which then diffuses away to the flagellum where it modulates motor rotation. Adaptation to continuous stimulation is mediated by a methyltransferase CheR. Together, these proteins represent an evolutionarily conserved core of the chemotaxis pathway, common to many bacteria and archaea (Kentner and Sourjik, 2006; Hazelbauer et al., 2008). Homologs of all these proteins are present in the *L. longbeachae* genomes (Cazalet et al., 2010; Kozak et al., 2010) and a similar chemotaxis system is present in *Legionella drancourtii* LLAP12 (La Scola et al., 2004) but it is absent from *L. pneumophila*. The flanking genomic regions are highly conserved

among *L. longbeachae* and all *L. pneumophila* strains sequenced, suggesting that *L. pneumophila*, although it encodes flagella has lost the chemotaxis system encoding genes by deletion events.

Thus these two species differ markedly in their surface structures. *L. longbeachae* encodes a capsule-like structure, synthesizes a very different LPS, does not synthesize flagella but encodes a chemotaxis system. These differences in surface structures seem to be due to deletion events leading to the loss of flagella in *L. longbeachae* and the loss of chemotaxis in *L. pneumophila* leading in part to the adaptation to their different main niches, soil, and water.

EVOLUTION OF EUKARYOTIC EFFECTORS – ACQUISITION BY HORIZONTAL GENE TRANSFER FROM EUKARYOTES?

Human to human transmission of *Legionella* has never been reported. Thus humans have been inconsequential in the evolution of these bacteria. However, *Legionella* have co-evolved with freshwater protozoa allowing the adaptation to eukaryotic cells. The idea that protozoa are training grounds for intracellular pathogens was born with the finding by Rowbotham (1980) that *Legionella* has the ability to multiply intracellularly. This led to a new percept in microbiology: bacteria parasitize protozoa and can utilize the same process to infect humans. Indeed, the long co-evolution of *Legionella* with protozoa is reflected in its genome by the presence of eukaryotic like genes, many of which are clearly virulence factors used by *L. pneumophila* to subvert host functions. These genes may have been acquired either through horizontal gene transfer (HGT) from the host cells (e.g., aquatic protozoa) or from bacteria or may have evolved by convergent evolution. Recently it has



been reported that *L. drancourtii* a relative of *L. pneumophila* has acquired a sterol reductase gene from the *Acanthamoeba polyphaga* *Mimivirus* genome, a virus that grows in amoeba (Moliner et al., 2009). Thus, the acquisition of some of the eukaryotic like genes of *L. pneumophila* by HGT from protozoa is plausible. *ralF* was the first gene suggested to have been acquired by *L. pneumophila* from eukaryotes by HGT, as *RalF* carries a eukaryotic Sec 7 domain (Nagai et al., 2002). In order to study the evolutionary origin of eukaryotic *L. pneumophila* genes, we have undertaken a phylogenetic analysis of the eukaryote-like sphingosine-1-phosphate lyase of *L. pneumophila* that is encoded by *lpp2128* described earlier. The phylogenetic analyses shown in Figure 4 revealed that it was most likely acquired from a eukaryotic organism early during *Legionella* evolution (Degtyar et al., 2009; Nora et al., 2009) as the *Lpp2128* protein sequence of *L. pneumophila* clearly falls into the eukaryotic clade of SPL sequences.

We then tested the hypothesis that *L. longbeachae* might have acquired genes also from plants, which is conceivable as it is found in soil. We thus undertook here a phylogenetic analysis similar to that described above for the *L. longbeachae* protein Llo2643 that contains PPR repeats, a protein family typically present in plants. A Blast search in the database revealed that homologs of Llo2643 are only found in eukaryotes, in particular in plants and algae. The only prokaryotes encoding this protein are the cyanobacteria *Microcoelus vaginatus* and *Cylindrospermopsis rasiborskii*. This rare presence in bacteria is suggestive of a horizontal transfer event from eukaryotes to these bacteria. Figure 5 shows the phylogenetic tree we obtained. The fact that the bacterial proteins group together may also be due to a phenomenon of long branch attraction. Thus, the Llo2643 protein of *L. longbeachae* appears closer to plant proteins than prokaryotic ones. Once more plant proteins, perhaps from algae, will be in the database, it might become possible to evaluate whether *L. longbeachae* indeed acquired genes from plants.

Legionella is not the only prokaryote whose genome shows an enrichment of proteins with eukaryotic domains. Another

example is the genome of “*Ca. Amoebophilus asiaticus*” a Gram-negative, obligate intracellular amoeba symbiont belonging to the *Bacteroidetes*, which has been discovered within an amoeba isolated from lake sediment (Schmitz-Esser et al., 2008) has been reported (Schmitz-Esser et al., 2010). In a recent report Schmitz-Esser et al. (2010) show that the genome of this organism also encodes an arsenal of proteins with eukaryotic domains. To further investigate the distribution of these protein domains in other bacteria the authors have undertaken an enrichment analysis comparing the fraction of all functional protein domains among 514 bacterial proteomes (Schmitz-Esser et al., 2010). This showed that the genomes of bacteria for which the replication in amoeba has been demonstrated were enriched in protein domains that are predominantly found in eukaryotic proteins. Interestingly, the domains potentially involved in host cell interaction described above, such as ANK repeats, LRR, SEL1 repeats, and F- and U-box domains, are among the most highly enriched domains in proteomes of amoeba-associated bacteria. Bacteria that can exploit amoebae as hosts thus share a set of eukaryotic domains important for host cell interaction despite their different lifestyles and their large phylogenetic diversity. This suggests that bacteria thriving within amoeba use similar mechanisms for host cell interaction to facilitate survival in the host cell. Due to the phylogenetic diversity of these bacteria, it is most likely that these traits were acquired independently during evolutionary early interaction with ancient protozoa.

CONCLUSION

Legionella pneumophila and *L. longbeachae* are two human pathogens that are able to modulate, manipulate, and subvert many eukaryotic host cell functions to their advantage, in order to enter, replicate, and evade protozoa or human alveolar macrophages during disease. In the last years genome analyses, as well as comparative and functional genomics have demonstrated that genome plasticity plays a major role in differences in host cell exploitation and niche adaptation of *Legionella*. The genomes of these environmental pathogens are shaped by HGT between

eukaryotes and prokaryotes, allowing them to mimic host cell functions and to exploit host cell pathways. Genome plasticity and HGT lead in each strain and species to a different repertoire of secreted effectors that may allow subtle adaptations to, e.g., different protozoan hosts. Plasmids can be exchanged among strains and phages and deletions of surface structures like flagella or chemotaxis systems has taken place. Thus genome plasticity is major mechanism by which *Legionella* may adapt to different niches and hosts.

Access to genomic data has revealed many potential virulence factors of *L. pneumophila* and *L. longbeachae* as well as metabolic capacities of these bacteria. The increasing information in the genomic database will allow a better identification of the origin and similarity of eukaryotic like proteins or eukaryotic protein domains and other virulence factors. New eukaryotic genomes like that of the natural host of *Legionella*, *A. castellanii* are in progress. These additional data will allow studying possible transfer events of genes from the eukaryotic host to *Legionella* more in depth. Taken together, the progressive increase of information on *Legionella* as well as on protozoa will allow more complete

comparative and phylogenetic studies to shed light on the evolution of virulence in *Legionella*. However, much work remains to be done to translate the basic findings from genomics research into improved understanding of the biology of this organism. As data are accumulating, new fields of investigation will emerge. Without doubt the investigation and characterization of regulatory ncRNAs will be one such field. Manipulation of host-epigenetic information and investigating host susceptibility to disease will be another. In particular development of high throughput techniques for comparative and functional genomics as well as more and more powerful imaging techniques will accelerate the pace of knowledge acquisition.

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REFERENCES

- Al-Khodori, S., Price, C. T., Habyarimana, F., Kalia, A., and Abu Kwaik, Y. (2008). A Dot/Icm-translocated ankyrin protein of *Legionella pneumophila* is required for intracellular proliferation within human macrophages and protozoa. *Mol. Microbiol.* 70, 908–923.
- Amodeo, M. R., Murdoch, D. R., and Pithie, A. D. (2009). Legionnaires' disease caused by *Legionella longbeachae* and *Legionella pneumophila*: comparison of clinical features, host-related risk factors, and outcomes. *Clin. Microbiol. Infect.* 16, 1405–1407.
- Anonymous. (1997). Legionellosis. *Commun. Dis. Intell.* 21, 137.
- Asare, R., and Abu Kwaik, Y. (2007). Early trafficking and intracellular replication of *Legionella longbeachae* within an ER-derived late endosome-like phagosome. *Cell. Microbiol.* 9, 1571–1587.
- Asare, R., Santic, M., Gobin, I., Doric, M., Suttles, J., Graham, J. E., Price, C. D., and Abu Kwaik, Y. (2007). Genetic susceptibility and caspase activation in mouse and human macrophages are distinct for *Legionella longbeachae* and *L. pneumophila*. *Infect. Immun.* 75, 1933–1945.
- Berger, K. H., and Isberg, R. R. (1993). Two distinct defects in intracellular growth complemented by a single genetic locus in *Legionella pneumophila*. *Mol. Microbiol.* 7, 7–19.
- Bibb, W. F., Sorg, R. J., Thomason, B. M., Hicklin, M. D., Steigerwalt, A. G., Brenner, D. J., and Wulf, M. R. (1981). Recognition of a second serogroup of *Legionella longbeachae*. *J. Clin. Microbiol.* 14, 674–677.
- Brombacher, E., Urwyler, S., Ragaz, C., Weber, S. S., Kami, K., Overduin, M., and Hilbi, H. (2009). Rab1 guanine nucleotide exchange factor SidM is a major phosphatidylinositol 4-phosphate-binding effector protein of *Legionella pneumophila*. *J. Biol. Chem.* 284, 4846–4856.
- Bruggemann, H., Cazalet, C., and Buchrieser, C. (2006). Adaptation of *Legionella pneumophila* to the host environment: role of protein secretion, effectors and eukaryotic-like proteins. *Curr. Opin. Microbiol.* 9, 86–94.
- Burstein, D., Zusman, T., Degtyar, E., Viner, R., Segal, G., and Pupko, T. (2009). Genome-scale identification of *Legionella pneumophila* effectors using a machine learning approach. *PLoS Pathog.* 5, e1000508. doi:10.1371/journal.ppat.1000508
- Campodonico, E. M., Chesnel, L., and Roy, C. R. (2005). A yeast genetic system for the identification and characterization of substrate proteins transferred into host cells by the *Legionella pneumophila* Dot/Icm system. *Mol. Microbiol.* 56, 918–933.
- Casati, S., Gioria-Martinoni, A., and Gaia, V. (2009). Commercial potting soils as an alternative infection source of *Legionella pneumophila* and other *Legionella* species in Switzerland. *Clin. Microbiol. Infect.* 15, 571–575.
- Cazalet, C., Gomez-Valero, L., Rusniok, C., Lomma, M., Dervins-Ravault, D., Newton, H. J., Sansom, F. M., Jarraud, S., Zidane, N., Ma, L., Bouchier, C., Etienne, J., Hartland, E. L., and Buchrieser, C. (2010). Analysis of the *Legionella longbeachae* genome and transcriptome uncovers unique strategies to cause Legionnaires' disease. *PLoS Genet.* 6, e1000851. doi:10.1371/journal.pgen.1000851
- Cazalet, C., Jarraud, S., Ghavi-Helm, Y., Kunst, F., Glaser, P., Etienne, J., and Buchrieser, C. (2008). Multigenome analysis identifies a worldwide distributed epidemic *Legionella pneumophila* clone that emerged within a highly diverse species. *Genome Res.* 18, 431–441.
- Cazalet, C., Rusniok, C., Bruggemann, H., Zidane, N., Magnier, A., Ma, L., Tichit, M., Jarraud, S., Bouchier, C., Vandenesch, F., Kunst, F., Etienne, J., Glaser, P., and Buchrieser, C. (2004). Evidence in the *Legionella pneumophila* genome for exploitation of host cell functions and high genome plasticity. *Nat. Genet.* 36, 1165–1173.
- Chen, J., De Felipe, K. S., Clarke, M., Lu, H., Anderson, O. R., Segal, G., and Shuman, H. A. (2004). *Legionella* effectors that promote nonlytic release from protozoa. *Science* 303, 1358–1361.
- Chien, M., Morozova, I., Shi, S., Sheng, H., Chen, J., Gomez, S. M., Asamani, G., Hill, K., Nuara, J., Feder, M., Rineer, J., Greenberg, J. J., Steshenko, V., Park, S. H., Zhao, B., Teplitskaya, E., Edwards, J. R., Pampou, S., Georgiou, A., Chou, I. C., Iannuccilli, W., Ulz, M. E., Kim, D. H., Geringer-Sameth, A., Goldsberry, C., Morozov, P., Fischer, S. G., Segal, G., Qu, X., Rzhetsky, A., Zhang, P., Cayanis, E., De Jong, P. J., Ju, J., Kalachikov, S., Shuman, H. A., and Russo, J. J. (2004). The genomic sequence of the accidental pathogen *Legionella pneumophila*. *Science* 305, 1966–1968.
- Cianciotto, N. P. (2009). Many substrates and functions of type II secretion: lessons learned from *Legionella pneumophila*. *Future Microbiol.* 4, 797–805.
- D'Auria, G., Jimenez-Hernandez, N., Peris-Bondia, F., Moya, A., and Latorre, A. (2010). *Legionella pneumophila* pangenome reveals strain-specific virulence factors. *BMC Genomics* 11, 181. doi:10.1186/1471-2164-11-181
- De Felipe, K. S., Glover, R. T., Charpentier, X., Anderson, O. R., Reyes, M., Pericone, C. D., and Shuman, H. A. (2008). *Legionella* eukaryotic-like type IV substrates interfere with organelle trafficking. *PLoS Pathog.* 4, e1000117. doi:10.1371/journal.ppat.1000117
- De Felipe, K. S., Pampou, S., Jovanovic, O. S., Pericone, C. D., Ye, S. F., Kalachikov, S., and Shuman, H. A. (2005). Evidence for acquisition of *Legionella* type IV secretion substrates via interdomain horizontal gene transfer. *J. Bacteriol.* 187, 7716–7726.

- Debroy, S., Dao, J., Soderberg, M., Rossier, O., and Cianciotto, N. P. (2006). *Legionella pneumophila* type II secretome reveals unique exoproteins and a chitinase that promotes bacterial persistence in the lung. *Proc. Natl. Acad. Sci. U.S.A.* 103, 19146–19151.
- Degtyar, E., Zusman, T., Ehrlich, M., and Segal, G. (2009). A *Legionella* effector acquired from protozoa is involved in sphingolipids metabolism and is targeted to the host cell mitochondria. *Cell. Microbiol.* 11, 1219–1235.
- Diez, E., Lee, S. H., Gauthier, S., Yaraghi, Z., Tremblay, M., Vidal, S., and Gros, P. (2003). Birc1e is the gene within the Lgn1 locus associated with resistance to *Legionella pneumophila*. *Nat. Genet.* 33, 55–60.
- Doleans, A., Aurell, H., Reyrolle, M., Lina, G., Freney, J., Vandenesch, F., Etienne, J., and Jarraud, S. (2004). Clinical and environmental distributions of *Legionella* strains in France are different. *J. Clin. Microbiol.* 42, 458–460.
- Edelstein, P. H., and Metlay, J. P. (2009). *Legionella pneumophila* goes clonal – Paris and Lorraine strain-specific risk factors. *Clin. Infect. Dis.* 49, 192–194.
- Eiserich, J. P., Estévez, A. G., Bamberg, T. V., Ye, Y. Z., Chumley, P. H., Beckman, J. S., and Freeman, B. A. (1999). Microtubule dysfunction by posttranslational nitrotyrosination of alpha-tubulin: a nitric oxide-dependent mechanism of cellular injury. *Proc. Natl. Acad. Sci. U.S.A.* 96, 6365–6370.
- Feldman, M., and Segal, G. (2004). A specific genomic location within the *icm/dot* pathogenesis region of different *Legionella* species encodes functionally similar but nonhomologous virulence proteins. *Infect. Immun.* 72, 4503–4511.
- Feldman, M., Zusman, T., Hagag, S., and Segal, G. (2005). Coevolution between nonhomologous but functionally similar proteins and their conserved partners in the *Legionella* pathogenesis system. *Proc. Natl. Acad. Sci. U.S.A.* 102, 12206–12211.
- Fernandez-Moreira, E., Helbig, J. H., and Swanson, M. S. (2006). Membrane vesicles shed by *Legionella pneumophila* inhibit fusion of phagosomes with lysosomes. *Infect. Immun.* 74, 3285–3295.
- Fraser, D. W., Tsai, T. R., Orenstein, W., Parkin, W. E., Beecham, H. J., Sharar, R. G., Harris, J., Mallison, G. F., Martin, S. M., Mcdade, J. E., Shepard, C. C., and Brachman, P. S. (1977). Legionnaires' disease: description of an epidemic of pneumonia. *N. Engl. J. Med.* 297, 1189–1197.
- Garcia, C., Ugalde, E., Campo, A. B., Minambres, E., and Kovacs, N. (2004). Fatal case of community-acquired pneumonia caused by *Legionella longbeachae* in a patient with systemic lupus erythematosus. *Eur. J. Clin. Microbiol. Infect. Dis.* 23, 116–118.
- Gobin, I., Susa, M., Begic, G., Hartland, E. L., and Doric, M. (2009). Experimental *Legionella longbeachae* infection in intratracheally inoculated mice. *J. Med. Microbiol.* 58, 723–730.
- Habyarimana, F., Price, C. T., Santic, M., Al-Khodori, S., and Kwai, Y. A. (2010). Molecular characterization of the Dot/Icm-translocated AnkH and AnkJ eukaryotic-like effectors of *Legionella pneumophila*. *Infect. Immun.* 78, 1123–1134.
- Hazelbauer, G. L., Falke, J. J., and Parkinson, J. S. (2008). Bacterial chemoreceptors: high-performance signaling in networked arrays. *Trends Biochem. Sci.* 33, 9–19.
- Heidtman, M., Chen, E. J., Moy, M. Y., and Isberg, R. R. (2009). Large-scale identification of *Legionella pneumophila* Dot/Icm substrates that modulate host cell vesicle trafficking pathways. *Cell. Microbiol.* 11, 230–248.
- Herrmann, V., Eidner, A., Rydzewski, K., Bladel, I., Jules, M., Buchrieser, C., Eisenreich, W., and Heuner, K. (2011). GamA is a eukaryotic-like glucoamylase responsible for glycogen- and starch-degrading activity of *Legionella pneumophila*. *Int. J. Med. Microbiol.* 301, 133–139.
- Hubber, A., and Roy, C. R. (2010). Modulation of host cell function by *Legionella pneumophila* type IV effectors. *Annu. Rev. Cell Dev. Biol.* 26, 261–283.
- Ingmundson, A., Delprato, A., Lambright, D. G., and Roy, C. R. (2007). *Legionella pneumophila* proteins that regulate Rab1 membrane cycling. *Nature* 450, 365–369.
- Isberg, R. R., O'Connor, T. J., and Heidtman, M. (2009). The *Legionella pneumophila* replication vacuole: making a cosy niche inside host cells. *Nat. Rev. Microbiol.* 7, 13–24.
- Kentner, D., and Sourjik, V. (2006). Spatial organization of the bacterial chemotaxis system. *Curr. Opin. Microbiol.* 9, 619–624.
- Kozak, N. A., Buss, M., Lucas, C. E., Frace, M., Govil, D., Travis, T., Olsen-Rasmussen, M., Benson, R. F., and Fields, B. S. (2010). Virulence factors encoded by *Legionella longbeachae* identified on the basis of the genome sequence analysis of clinical isolate D-4968. *J. Bacteriol.* 192, 1030–1044.
- Kubori, T., Hyakutake, A., and Nagai, H. (2008). *Legionella* translocates an E3 ubiquitin ligase that has multiple Ubiquitin ligase with distinct functions. *Mol. Microbiol.* 67, 1307–1319.
- Kubori, T., Shinzawa, N., Kanuka, H., and Nagai, H. (2010). *Legionella* metaeffector exploits host proteasome to temporally regulate cognate effector. *PLoS Pathog.* 6, e1001216. doi:10.1371/journal.ppat.1001216
- Kubota, M., Tomii, K., Tachikawa, R., Harada, Y., Seo, R., Kaji, R., Takeshima, Y., Hayashi, M., Nishimura, T., and Ishihara, K. (2007). *Legionella longbeachae* pneumonia infection from home garden soil. *Nihon Kokyuki Gakkai Zasshi* 45, 698–703.
- Kumpers, P., Tiede, A., Kirschner, P., Girke, J., Ganser, A., and Peest, D. (2008). Legionnaires' disease in immunocompromised patients: a case report of *Legionella longbeachae* pneumonia and review of the literature. *J. Med. Microbiol.* 57, 384–387.
- La Scola, B., Birtles, R. J., Greub, G., Harrison, T. J., Ratcliff, R. M., and Raoult, D. (2004). *Legionella drancourtii* sp. nov., a strictly intracellular amoebal pathogen. *Int. J. Syst. Evol. Microbiol.* 54, 699–703.
- Lamkanfi, M., Amer, A., Kanneganti, T. D., Munoz-Planillo, R., Chen, G., Vandenabeele, P., Fortier, A., Gros, P., and Nunez, G. (2007). The Nod-like receptor family member Naip5/Birc1e restricts *Legionella pneumophila* growth independently of caspase-1 activation. *J. Immunol.* 178, 8022–8027.
- Lightfield, K. L., Persson, J., Brubaker, S. W., Witte, C. E., Von Moltke, J., Dunipace, E. A., Henry, T., Sun, Y. H., Cado, D., Dietrich, W. F., Monack, D. M., Tsolis, R. M., and Vance, R. E. (2008). Critical function for Naip5 in inflammasome activation by a conserved carboxy-terminal domain of flagellin. *Nat. Immunol.* 9, 1171–1178.
- Liu, Y., and Luo, Z. Q. (2007). The *Legionella pneumophila* effector SidJ is required for efficient recruitment of endoplasmic reticulum proteins to the bacterial phagosome. *Infect. Immun.* 75, 592–603.
- Lomma, M., Dervins-Ravault, D., Rolando, M., Nora, T., Newton, H. J., Sansom, F. M., Sahr, T., Gomez-Valero, L., Jules, M., Hartland, E. L., and Buchrieser, C. (2010). The *Legionella pneumophila* F-box protein Lpp2082 (AnkB) modulates ubiquitination of the host protein parvin B and promotes intracellular replication. *Cell. Microbiol.* 12, 1272–1291.
- Luo, Z. Q. (2011). Targeting one of its own: expanding roles of substrates of the *Legionella pneumophila* Dot/Icm type IV secretion system. *Front. Microbiol.* 2:31. doi:10.3389/fmicb.2011.00031
- Luo, Z. Q., and Isberg, R. R. (2004). Multiple substrates of the *Legionella pneumophila* Dot/Icm system identified by interbacterial protein transfer. *Proc. Natl. Acad. Sci. U.S.A.* 101, 841–846.
- Lurin, C., Andrés, C., Aubourg, S., Bellaoui, M., Bitton, F., Bruyère, C., Caboche, M., Debast, C., Gualberto, J., Hoffmann, B., Lecharny, A., Le Ret, M., Martin-Magniette, M. L., Mireau, H., Peeters, N., Renou, J. P., Szurek, B., Taconnat, L., and Small, I. (2004). Genome-wide analysis of *Arabidopsis* pentatricopeptide repeat proteins reveals their essential role in organelle biogenesis. *Plant Cell* 16, 2089–2103.
- Machner, M. P., and Isberg, R. R. (2006). Targeting of host Rab GTPase function by the intravacuolar pathogen *Legionella pneumophila*. *Dev. Cell* 11, 47–56.
- Machner, M. P., and Isberg, R. R. (2007). A bifunctional bacterial protein links GDI displacement to Rab1 activation. *Science* 318, 974–977.
- Marra, A., Blander, S. J., Horwitz, M. A., and Shuman, H. A. (1992). Identification of a *Legionella pneumophila* locus required for intracellular multiplication in human macrophages. *Proc. Natl. Acad. Sci. U.S.A.* 89, 9607–9611.
- Marrie, T. J. (2008). "Legionnaires' disease – clinical picture," in *Legionella pneumophila: Pathogenesis and Immunity*, eds P. Hoffmann, H. Friedman and M. Bendinelli (New York: Springer), 133–150.
- Mcdade, J. E., Shepard, C. C., Fraser, D. W., Tsai, T. R., Redus, M. A., and Dowdle, W. R. (1977). Legionnaires' disease: isolation of a bacterium and demonstration of its role in other respiratory disease. *N. Engl. J. Med.* 297, 1197–1203.
- McKinney, R. M., Porschen, R. K., Edelstein, P. H., Bissett, M. L., Harris, P. P., Bondell, S. P., Steigerwald, A. G., Weaver, R. E., Ein, M. E., Lindquist, D. S., Kops, R. S., and Brenner, D. J. (1981). *Legionella longbeachae* species nova, another etiologic agent of human pneumonia. *Ann. Intern. Med.* 94, 739–743.

- MMWR. (2000). Legionnaires' disease associated with potting soil – California, Oregon, and Washington, May–June 2000. *Morb. Mortal. Wkly. Rep.* 49, 777–778.
- Moliner, C., Ginevra, C., Jarraud, S., Flaudrops, C., Bedotto, M., Coudere, C., Etienne, J., and Fournier, P. E. (2009). Rapid identification of *Legionella* species by mass spectrometry. *J. Med. Microbiol.* 59(Pt 3), 273–284.
- Molofsky, A. B., Byrne, B. G., Whitfield, N. N., Madigan, C. A., Fuse, E. T., Tateda, K., and Swanson, M. S. (2006). Cytosolic recognition of flagellin by mouse macrophages restricts *Legionella pneumophila* infection. *J. Exp. Med.* 197, 1093–1104.
- Molofsky, A. B., and Swanson, M. S. (2004). Differentiate to thrive: lessons from the *Legionella pneumophila* life cycle. *Mol. Microbiol.* 53, 29–40.
- Montanaro-Punzengruber, J. C., Hicks, L., Meyer, W., and Gilbert, G. L. (1999). Australian isolates of *Legionella longbeachae* are not a clonal population. *J. Clin. Microbiol.* 37, 3249–3254.
- Morozova, I., Qu, X., Shi, S., Asamani, G., Greenberg, J. E., Shuman, H. A., and Russo, J. J. (2004). Comparative sequence analysis of the *icm/dot* genes in *Legionella*. *Plasmid* 51, 127–147.
- Müller, M. P., Peters, H., Blümer, J., Blankenfeldt, W., Goody, R. S., and Itzen, A. (2010). The *Legionella* effector protein DrrA AMPylates the membrane traffic regulator Rab1b. *Science* 329, 946–949.
- Murata, T., Delprato, A., Ingmundson, A., Toomre, D. K., Lambright, D. G., and Roy, C. R. (2006). The *Legionella pneumophila* effector protein DrrA is a Rab1 guanine nucleotide-exchange factor. *Nat. Cell Biol.* 8, 971–977.
- Nagai, H., Cambronne, E. D., Kagan, J. C., Amor, J. C., Kahn, R. A., and Roy, C. R. (2005). A C-terminal translocation signal required for Dot/Icm-dependent delivery of the *Legionella* RalF protein to host cells. *Proc. Natl. Acad. Sci. U.S.A.* 102, 826–831.
- Nagai, H., Kagan, J. C., Zhu, X., Kahn, R. A., and Roy, C. R. (2002). A bacterial guanine nucleotide exchange factor activates ARF on *Legionella* phagosomes. *Science* 295, 679–682.
- Nagai, H., and Kubori, T. (2011). Type IVB secretion systems of *Legionella* and other Gram-negative bacteria. *Front. Microbiol.* 2:136. doi:10.3389/fmicb.2011.00136
- Nakamura, T., Schuster, G., Sugiura, M., and Sugita, M. (2004). Chloroplast RNA-binding and pentatricopeptide repeat proteins. *Biochem. Soc. Trans.* 32, 571–574.
- Neunuebel, M. R., Chen, Y., Gaspar, A. H., Backlund, P. S. Jr., Yergey, A., and Machner, M. P. (2011). De-AMPylation of the small GTPase Rab1 by the pathogen *Legionella pneumophila*. *Science* 333, 453–456.
- Newton, H. J., Sansom, F. M., Dao, J., Mcalister, A. D., Sloan, J., Cianciotto, N. P., and Hartland, E. L. (2007). Sel1 repeat protein LpnE is a *Legionella pneumophila* virulence determinant that influences vacuolar trafficking. *Infect. Immun.* 75, 5575–5585.
- Ninio, S., Celli, J., and Roy, C. R. (2009). A *Legionella pneumophila* effector protein encoded in a region of genomic plasticity binds to Dot/Icm-modified vacuoles. *PLoS Pathog.* 5, e1000278. doi:10.1371/journal.ppat.1000278
- Nora, T., Lomma, M., Gomez-Valero, L., and Buchrieser, C. (2009). Molecular mimicry: an important virulence strategy employed by *Legionella pneumophila* to subvert host functions. *Future Microbiol.* 4, 691–701.
- O'Connor, B. A., Carman, J., Eckert, K., Tucker, G., Givney, R., and Cameron, S. (2007). Does using potting mix make you sick? Results from a *Legionella longbeachae* case-control study in South Australia. *Epidemiol. Infect.* 135, 34–39.
- Pan, X., Lührmann, A., Satoh, A., Laskowski-Arce, M. A., and Roy, C. R. (2008). Ankyrin repeat proteins comprise a diverse family of bacterial type IV effectors. *Science* 320, 1651–1654.
- Pravinkumar, S., Edwards, G., Lindsay, D., Redmond, S., Stirling, J., House, R., Kerr, J., Anderson, E., Breen, D., Blatchford, O., McDonald, E., and Brown, A. (2010). A cluster of Legionnaires' disease caused by *Legionella longbeachae* linked to potting compost in Scotland, 2008–2009. *Euro Surveill.* 15, 19496.
- Price, C. T., Al-Khodori, S., Al-Quadani, T., Santic, M., Habyarimana, F., Kalia, A., and Kwai, Y. A. (2009). Molecular mimicry by an F-Box Effector of *Legionella pneumophila* hijacks a conserved polyubiquitination machinery within macrophages and protozoa. *PLoS Pathog.* 5, e1000704. doi:10.1371/journal.ppat.1000704
- Ren, T., Zamboni, D. S., Roy, C. R., Dietrich, W. F., and Vance, R. E. (2006). Flagellin-deficient *Legionella* mutants evade caspase-1- and Naip5-mediated macrophage immunity. *PLoS Pathog.* 2, e18. doi:10.1371/journal.ppat.0020018
- Rossier, O., and Cianciotto, N. P. (2001). Type II protein secretion is a subset of the PilD-dependent processes that facilitate intracellular infection by *Legionella pneumophila*. *Infect. Immun.* 69, 2092–2098.
- Rowbotham, T. J. (1980). Preliminary report on the pathogenicity of *Legionella pneumophila* for freshwater and soil amoebae. *J. Clin. Pathol.* 33, 1179–1183.
- Sahr, T., Bruggemann, H., Jules, M., Lomma, M., Albert-Weissenberger, C., Cazalet, C., and Buchrieser, C. (2009). Two small ncRNAs jointly govern virulence and transmission in *Legionella pneumophila*. *Mol. Microbiol.* 72, 741–762.
- Sansom, F. M., Newton, H. J., Crikis, S., Cianciotto, N. P., Cowan, P. J., D'Apice, A. J., and Hartland, E. L. (2007). A bacterial ecto-triphosphate diphosphohydrolase similar to human CD39 is essential for intracellular multiplication of *Legionella pneumophila*. *Cell. Microbiol.* 9, 1922–1935.
- Sansom, F. M., Riedmaier, P., Newton, H. J., Dunstone, M. A., Müller, C. E., Stephan, H., Byres, E., Beddoe, T., Rossjohn, J., Cowan, P. J., D'Apice, A. J., Robson, S. C., and Hartland, E. L. (2008). Enzymatic properties of an ecto-nucleoside triphosphate diphosphohydrolase from *Legionella pneumophila*: substrate specificity and requirement for virulence. *J. Biol. Chem.* 283, 12909–12918.
- Schmitz-Esser, S., Tischler, P., Arnold, R., Montanaro, J., Wagner, M., Rattei, T., and Horn, M. (2010). The genome of the amoeba symbiont “*Candidatus Amoebophilus asiaticus*” reveals common mechanisms for host cell interaction among amoeba-associated bacteria. *J. Bacteriol.* 192, 1045–1057.
- Schmitz-Esser, S., Toenshoff, E. R., Haider, S., Heinz, E., Hoenninger, V. M., Wagner, M., and Horn, M. (2008). Diversity of bacterial endosymbionts of environmental *Acanthamoeba* isolates. *Appl. Environ. Microbiol.* 74, 5822–5831.
- Schmitz-Linneweber, C., and Small, I. (2008). Pentatricopeptide repeat proteins: a socket set for organelle gene expression. *Trends Plant Sci.* 13, 663–670.
- Schroeder, G. N., Petty, N. K., Mounier, A., Harding, C. R., Vogrin, A. J., Wee, B., Fry, N. K., Harrison, T. G., Newton, H. J., Thomson, N. R., Beatson, S. A., Dougan, G., Hartland, E. L., and Frankel, G. (2010). *Legionella pneumophila* strain 130b possesses a unique combination of type IV secretion systems and novel Dot/Icm secretion system effector proteins. *J. Bacteriol.* 192, 6001–6016.
- Schuelein, R., Ang, D. K., Van Driel, I. R., and Hartland, E. L. (2011). Immune control of *Legionella* infection: an in vivo perspective. *Front. Microbiol.* 2:126. doi:10.3389/fmicb.2011.00126
- Segal, G., Feldman, M., and Zisman, T. (2005). The Icm/Dot type-IV secretion systems of *Legionella pneumophila* and *Coxiella burnetii*. *FEMS Microbiol. Rev.* 29, 65–81.
- Segal, G., Russo, J. J., and Shuman, H. A. (1999). Relationships between a new type IV secretion system and the *icm/dot* virulence system of *Legionella pneumophila*. *Mol. Microbiol.* 34, 799–809.
- Shin, S., and Roy, C. R. (2008). Host cell processes that influence the intracellular survival of *Legionella pneumophila*. *Cell. Microbiol.* 10, 1209–1220.
- Shohdy, N., Efe, J. A., Emr, S. D., and Shuman, H. A. (2005). Pathogen effector protein screening in yeast identifies *Legionella* factors that interfere with membrane trafficking. *Proc. Natl. Acad. Sci. U.S.A.* 102, 4866–4871.
- Steele, T. W., Moore, C. V., and Sangster, N. (1990). Distribution of *Legionella longbeachae* serogroup 1 and other legionellae in potting soils in Australia. *Appl. Environ. Microbiol.* 56, 2984–2988.
- Steinert, M., Hentschel, U., and Hacker, J. (2002). *Legionella pneumophila*: an aquatic microbe goes astray. *FEMS Microbiol. Rev.* 26, 149–162.
- Steinert, M., Heuner, K., Buchrieser, C., Albert-Weissenberger, C., and Glockner, G. (2007). *Legionella* pathogenicity: genome structure, regulatory networks and the host cell response. *Int. J. Med. Microbiol.* 297, 577–587.
- Tan, Y., and Luo, Z. Q. (2011). *Legionella pneumophila* SidD is a deAMPyase that modifies Rab1. *Nature* 475, 506–509.
- Tijet, N., Tang, P., Romilowich, M., Duncan, C., Ng, V., Fisman, D. N., Jamieson, F., Low, D. E., and Guyard, C. (2010). New endemic *Legionella pneumophila* serogroup I clones, Ontario, Canada. *Emerging Infect. Dis.* 16, 447–454.
- Velonakis, E. N., Kiousi, I. M., Koutis, C., Papadogiannakis, E., Babatsikou, F., and Vatopoulos, A. (2009). First isolation of *Legionella* species, including *L. pneumophila* serogroup 1, in Greek potting soils: possible importance for public health. *Clin. Microbiol. Infect.* 16, 763–766.

- Weber, S. S., Ragaz, C., and Hilbi, H. (2009). The inositol polyphosphate 5-phosphatase OCRL1 restricts intracellular growth of *Legionella*, localizes to the replicative vacuole and binds to the bacterial effector LpnE. *Cell. Microbiol.* 11, 442–460.
- Weber, S. S., Ragaz, C., Reus, K., Nyfeler, Y., and Hilbi, H. (2006). *Legionella pneumophila* exploits PI(4)P to anchor secreted effector proteins to the replicative vacuole. *PLoS Pathog.* 2, e46. doi:10.1371/journal.ppat.0020046
- Whiley, H., and Bentham, R. (2011). *Legionella longbeachae* and legionellosis. *Emerging Infect. Dis.* 17, 579–583.
- Wright, E. K., Goodart, S. A., Gowney, J. D., Hadinoto, V., Endrizzi, M. G., Long, E. M., Sadigh, K., Abney, A. L., Bernstein-Hanley, I., and Dietrich, W. F. (2003). Naip5 affects host susceptibility to the intracellular pathogen *Legionella pneumophila*. *Curr. Biol.* 13, 27–36.
- Yu, V. L., Plouffe, J. F., Pastoris, M. C., Stout, J. E., Schousboe, M., Widmer, A., Summersgill, J., File, T., Heath, C. M., Paterson, D. L., and Cheresky, A. (2002). Distribution of *Legionella* species and serogroups isolated by culture in patients with sporadic community-acquired legionellosis: an international collaborative survey. *J. Infect. Dis.* 186, 127–128.
- Zamboni, D. S., Kobayashi, K. S., Kohlsdorf, T., Ogura, Y., Long, E. M., Vance, R. E., Kuida, K., Mariathasan, S., Dixit, V. M., Flavell, R. A., Dietrich, W. F., and Roy, C. R. (2006). The Birc1e cytosolic pattern-recognition receptor contributes to the detection and control of *Legionella pneumophila* infection. *Nat. Immunol.* 7, 318–325.
- Zeigler, D. R. (2003). Gene sequences useful for predicting relatedness of whole genomes in bacteria. *Int. J. Syst. Evol. Microbiol.* 53, 1893–1900.
- Zhu, W., Banga, S., Tan, Y., Zheng, C., Stephenson, R., Gately, J., and Luo, Z. Q. (2011). Comprehensive identification of protein substrates of the Dot/Icm type IV transporter of *Legionella pneumophila*. *PLoS ONE* 6, e17638. doi:10.1371/journal.pone.0017638
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