Tetra- and Penta-Acylated Lipid A Structures of Porphyromonas gingivalis LPS Differentially Activate TLR4-Mediated NF-κB Signal Transduction Cascade and Immuno-Inflammatory Response in Human Gingival Fibroblasts

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Abstract

Background: Porphyromonas gingivalis is a major pathogen of periodontal disease that affects a majority of adults worldwide. Increasing evidence shows that periodontal disease is linked to various systemic diseases like diabetes and cardiovascular disease, by contributing to increased systemic levels of inflammation. Lipopolysaccharides (LPS), as a key virulent attribute of P. gingivalis, possesses significant amount of lipid A heterogeneity containing tetra- (LPS1435/1449) and penta-acylated (LPS1690) structures. Hitherto, the exact molecular mechanism of P. gingivalis LPS involved in periodontal pathogenesis remains unclear, due to limited understanding of the specific receptors and signaling pathways involved in LPS-host cell interactions.

Methodology/Principal Findings: This study systematically investigated the effects of P. gingivalis LPS1435/1449 and LPS1690 on the expression of TLR2 and TLR4 signal transduction and the activation of pro-inflammatory cytokines IL-6 and IL-8 in human gingival fibroblasts (HGFs). We found that LPS1435/1449 and LPS1690 differentially modulated TLR2 and TLR4 expression. NF-κB pathway was significantly activated by LPS1690 but not by LPS1435/1449. In addition, LPS1690 induced significant expression of NF-κB and p38 MAPK pathways-related genes, such as NFKBIA, NFKB1, IKBKB, MAP2K4 and MAPK8. Notably, the pro-inflammatory genes including GM-CSF, CKCL10, G-CSF, IL-6, IL-8 and CCL2 were significantly upregulated by LPS1690 while down-regulated by LPS1435/1449. Blocking assays confirmed that TLR4-mediated NF-κB signaling was vital in LPS1690-induced expression of IL-6 and IL-8 in HGFs.

Conclusions/Significance: The present study suggests that the tetra- and penta-acylated lipid A structures of P. gingivalis LPS differentially activate TLR4-mediated NF-κB signaling pathway, and significantly modulate the expression of IL-6 and IL-8 in HGFs. The ability to alter the lipid A structure of LPS could be one of the strategies carried out by P. gingivalis to evade innate host defense in gingival tissues, thereby contributing to periodontal pathogenesis.

Introduction

Periodontal disease is among the most common chronic infections and inflammatory events in humans, and severe periodontal disease (periodontitis) is the major cause of tooth loss in adults globally [1]. Porphyromonas gingivalis is considered a keystone bacterial pathogen strongly implicated in periodontal disease [2–4]. It is able to gain access to gingival tissues from pathogenic plaque biofilm and proliferate in gingival tissue, resulting in overt and unco-ordinated immuno-inflammatory response, and thereby leading to destruction of tooth supporting tissues [5,6]. Lipopolysaccharide (LPS) is a cell wall component of Gram-negative bacteria including, P. gingivalis. This biomolecule is considered to be a major nexus for virulence in periodontitis [3,7]. LPS basically consists of three segments with highly variable and conserved regions [8,9]. They are a phosphorylated glucosamine disaccharide substituted with fatty acids known as lipid A which forms the matrix of the outermost membrane leaflet, a highly
variable O-poly saccharide (O-antigen) and a conserved core oligosaccharide that links lipid A to the O-poly saccharide. Lipid A section is the ‘bioactive centre’ of LPS, responsible for its endotoxicity. This is due to the specific and highly sensitive recognition of lipid A by host cells, which subsequently leads to strong immuno-inflammatory response [7,9,10].

P. gingivalis releases copious amounts of LPS that penetrates gingival tissues [11,12] and actively participates in the pathogenic process of periodontitis [12–14]. Numerous studies in the past have examined the role of P. gingivalis LPS in periodontal pathogenesis. However, the precise nature of this relationship has been obscured due to lack of understanding of the underlying molecular mechanism of P. gingivalis LPS-host interaction. Some studies show that P. gingivalis LPS is a potent immune activator similar to the canonical E. coli LPS, whilst others report it to be immunologically inert [14,15]. Hence, according to some studies P. gingivalis LPS induces pro-inflammatory cytokines [16,17] whereas others argue that it may dampen the cytokine expression [18,19].

Cell surface receptors and signal transduction pathways involved in P. gingivalis LPS and host cell interaction is at the heart of this long-standing debate. Most early studies with canonical E. coli LPS, containing hexa-acylated lipid A structure, have shown that E. coli LPS exclusively binds to toll-like receptor-4 (TLR4) [20,21]. Although some claim that E. coli LPS may bind to TLR2, later studies showed that this was a result of lipoprotein contamination in LPS, since TLR2 is known to occupy the LPS lipid A [22]. This controversy is further fuelled by the findings on LPS containing heterogeneous lipid A structures of non-enterobacterial species such as, P. gingivalis, Bacteroides fragilis and Pseudomonas aeruginosa [23–26]. The common structural variation occurring in P. gingivalis LPS lipid A is due to the alteration of number of fatty acid chains attached to core disaccharide, which results in tetra- and penta-acylated structures [27,28]. Hence, P. gingivalis LPS possesses lipid A structure containing both tetra-acylated (PgLPS1415/1419) and penta-acylated forms (PgLPS1690) compared to the hexa-acylated lipid A of E. coli LPS. Cell surface receptors and signal transduction pathways involved in host responses to aforementioned heterogeneous lipid A structures are the focus of the present study.

The heterogeneous nature of LPS lipid A renders P. gingivalis an unusual ability to interact with both TLR2 and TLR4, in contrast to E. coli LPS. Structural variation in lipid A moieties of P. gingivalis LPS may also differentially activate signal transduction pathways to elicit various immuno-inflammatory responses. For instance, hexa-acylated E. coli LPS preferentially activates TLR4-NF-κB cascade, whereas heterogeneous P. gingivalis LPS may use different cellular signaling pathways to modulate downstream pro-inflammatory cytokines [17,29].

Controversial observations have been reported on P. gingivalis LPS-induced host response in various cell types that were investigated [30]. Most of the previous studies on P. gingivalis LPS have been performed in non-oral cells such as embryonic kidney cells, umbilical cord vein endothelial cells and monocytes [28,29,31,32]. Only a few studies have undertaken on the primary cells of dental origin, which are more likely to interact with P. gingivalis LPS in clinical situations [33,34]. Human gingival fibroblasts (HGFs) as the predominant structural cells in human gingiva represent a viable model to study P. gingivalis LPS-host interactions. Firstly, HGFs express a number of pattern recognition receptors known to orchestrate immuno-inflammatory response [35–37]. Secondly, different isoforms of P. gingivalis LPS differentially activate the expression of pro-inflammatory cytokines in HGFs as shown in our recent study [32]. Thirdly, HGFs play a pivotal role in the immuno-inflammatory response in the pathogenesis of periodontal disease [13,38,39].

The present study comprehensively investigated the effects of lipid A molecular heterogeneity of P. gingivalis LPS on the expression of TLR2 and TLR4, downstream signal transduction and on the activation of pro-inflammatory cytokines in HGFs. P. gingivalis LPS1415/1419 and LPS1690 differentially modulated TLR2 and TLR4 expression. LPS1690 induced significant expression of NF-κB and p38 MAPK pathways-related genes as well as multiple pro-inflammatory genes. TLR4 and NF-κB were significantly involved in P. gingivalis LPS1690-induced expression of IL-6 and IL-8. Our findings demonstrate that P. gingivalis LPS with tetra- and penta-acylated lipid A structures differentially activate TLR4-mediated NF-κB signaling pathway, and critically modulate immuno-inflammatory response in HGFs.

Results

P. gingivalis LPS1690 and LPS1415/1449 Differentially Modulated the Expression of TLR2, TLR4 and MD2

Transcripts in HGFs

HGFs were treated with E. coli LPS and P. gingivalis LPS (LPS1690 and LPS1415/1449) in both dose- and time-dependent experiments to examine the transcript expression of TLR2, TLR4, MD2 and MyD88. Basal expression of both TLR2 and TLR4 could be observed in the untreated cells which was upregulated by E. coli LPS and P. gingivalis LPS (Figs. 1 and 2). E. coli LPS and P. gingivalis LPS1690 (not LPS1415/1449) significantly upregulated TLR4 expression at 0.1 μg/ml or above (Fig. 1B), and the expression level reached the peak at 12 and 24 h, respectively (Fig. 1B2). Whereas, P. gingivalis LPS1415/1449 and to a less extent P. gingivalis LPS1690 significantly enhanced the TLR2 expression (Fig. 1A), and the peak expression was observed at 24 h (Fig. 1A2). E. coli LPS significantly upregulated CD14 and LBP expression (Figs. 1IC and D); MD2 was significantly upregulated by both P. gingivalis LPS1690 (not LPS1415/1449) and E. coli LPS (Figs. 1IE and 1IC2). Additionally, MyD88 increased markedly by the stimulation of E. coli LPS and to a much less extent by P. gingivalis LPS (Figs. 1IF and 1ID2). Foregoing data demonstrated that P. gingivalis LPS1690 and LPS1415/1449 could differentially modulate to a different extent the transcript expression of TLR2, TLR4 and MD2.

P. gingivalis LPS1690 and LPS1415/1449 Differentially Modulated the Expression of TLR2 and TLR4 Proteins in HGFs

Next, in a time-course experiment (5–120 min) the expression of TLR2 and TLR4 proteins in HGFs was analyzed by western blot. Both TLR2 and TLR4 proteins were detected in all samples confirming their basal expression (Fig. 2). P. gingivalis LPS1415/1449 induced the prompt expression of TLR2 protein at 5 and 15 min (Figs. 2A and D). While there was a cyclic TLR4 expression pattern in cells treated with P. gingivalis LPS1690 and E. coli LPS, which was observed at 5, 15 and 120 min, respectively (Figs. 2B, C and E). These data further demonstrated that the expression of TLR2 and TLR4 in HGFs was differentially modulated by heterogeneous lipid A structures of P. gingivalis LPS. The expression profiles of TLR2 and TLR4 were further examined by antibody-mediated confocal immuno-fluorescence microscopy. HGFs showed basal expression of both TLR2 and TLR4. Whereas, P. gingivalis LPS1415/1449 upregulated the basal expression of TLR2 at 6 and 24 h (Figs. 3.1 and S1.1). P. gingivalis LPS1690-upregulated expression of TLR2 was meager at 6 h.
1.1

A

Fold changes of TLR2 mRNA

LPS concentration (µg/mL)

Control 0.001 0.01 0.1 1 10

* * * * * *

B

Fold changes of TLR4 mRNA

LPS concentration (µg/mL)

Control 0.001 0.01 0.1 1 10

* * * * * *

C

Fold changes of CD14 mRNA

LPS concentration (µg/mL)

Control 0.001 0.01 0.1 1 10

* * * * * *

D

Fold changes of LBP mRNA

LPS concentration (µg/mL)

Control 0.001 0.01 0.1 1 10

* * * * * *

E

Fold changes of MD2 mRNA

LPS concentration (µg/mL)

Control 0.001 0.01 0.1 1 10

* * * * * *

F

Fold changes of MYD88 mRNA

LPS concentration (µg/mL)

Control 0.001 0.01 0.1 1 10

* * * * * *

1.2

A

Fold changes of TLR2 mRNA

Incubation time (h)

2 12 24 48

* * * * *

B

Fold changes of TLR4 mRNA

Incubation time (h)

2 12 24 48

* * * * *

C

Fold changes of MD2 mRNA

Incubation time (h)

2 12 24 48

* * * * *

D

Fold changes of MYD88 mRNA

Incubation time (h)

2 12 24 48

* * * * *
and became more prominent at 24 h, and only a scanty expression was noted in cells treated with \textit{E. coli} LPS at 24 h (Fig. S1.1). Relatively prompt and marked expression of TLR4 was observed in cells treated with PgLPS1690 and \textit{E. coli} LPS at 6 h (Fig. 3.2) and to a less extent at 24 h (Fig. S1.2). These findings were overall consistent with foregoing results (Figs. 1 and 2). No positive signal was detected in negative controls, suggesting that the antibodies employed were actually bound to TLR2 and TLR4, and the non-specific binding or background staining was negligible.

The Expression Profiles of Genes Associated with TLR Signal Transduction in HGFs induced by \textit{P. gingivalis} LPS1690 and LPS1435/1449

The potential modulation of other molecules involved in \textit{P. gingivalis} LPS-induced TLR signaling pathway was analyzed using PCR gene-array. Both \textit{P. gingivalis} LPS1690 and LPS1435/1449 significantly upregulated (fold changes $>2.0$) ELK1, HRAS, IL1B, TLR4, TLR5, TLR9, TNF, TRAF6 and UBE2N, and down regulated (fold changes <0.5) BTK, IL-2, IRAK1, LTA, CD180, MAPK8IP3, NFKBIL1, SIGIRR, TIRAP, TLR1 and TLR7 (Table S1). Notably, \textit{P. gingivalis} LPS1690 markedly upregulated
(≥3-folds) transcript levels of downstream pro-inflammatory genes, such as GM-CSF, CXCL10, G-CSF, IL-6, IL-8, CCL2 and TLR4, with reference to the untreated controls (Table 1 and Fig. S2). Moreover, P. gingivalis LPS1690 induced significant expression of NF-kB pathway-related genes such as NFKBIA, NFKB1 and IKKB as well as p38 MAPK pathway molecules such as MAP2K4 and MAPK8 (Table 1). Interestingly, the following genes were differentially up- (fold changes from 2.26 to 26.77) or down-regulated (fold changes from 0.06 to 0.67) by the two isoforms of P. gingivalis (LPS1690 v.s. LPS1435/1449), respectively: GM-CSF (26.77 v.s. 0.28), CXCL10 (17.27 vs. 0.21), G-CSF (14.91 vs. 0.67), IL-6 (11.93 vs. 0.06), IL-8 (8.64 vs. 0.35), CCL2 (3.25 vs. 0.58) and CD14 (2.26 vs. 0.45). To confirm some of the strongly upregulated pro-inflammatory cytokine and chemokine genes (≥3-folds) by P. gingivalis LPS1690, the expression of GM-CSF, CXCL10, IL-6 and IL-8 transcripts were further validated by real-time qPCR (Fig. S3).

P. gingivalis LPS1690 and LPS1435/1449 Differentially Determined the Activation of Intracellular Signal Transduction Pathways

The activation of NF-κB and MAPK signal pathways were examined by western blot in HGFs in response to the different isoforms of P. gingivalis LPS1690 and LPS1435/1449. As shown in Fig. 4, P. gingivalis LPS1690 and E. coli LPS induced the phosphorylation of IκBα and the p65 subunit of NF-κB. Both induced intense phosphorylation of IκBα after 15 min stimulation, which remained to be activated at 120 min (Figs. 4.1B–D). Comparably, P. gingivalis LPS1435/1449 induced only a weak activation of IκBα (Fig. 4.1A and D). There was a considerable level of constitutive expression of phosphorylated p65 in HGFs and the upregulation of p-p65 was marginal. However, activation of p65 subunit was observed promptly after 5 min stimulation of P. gingivalis LPS1690 and 30 min stimulation of E. coli LPS (Figs. 4.2B–D). No significant phosphorylation of p65 was activated by P. gingivalis LPS1435/1449 (Fig. 4.2A). Both P. gingivalis LPS1690 and LPS1435/1449 as well as E. coli LPS induced phosphorylation of p38 MAPK (Figs. 5.1A–C). P. gingivalis LPS1690 activated p38 MAPK at 15 min which lasted consistently until 120 min (Figs. 5.1B and D). Whereas, P. gingivalis LPS1435/1449 promptly activated the phosphorylation of p38 MAPK at 5 min and it remained significant until 120 min (Figs. 5.1A and D). Both P. gingivalis LPS and E. coli LPS activated ERK1/2 in a similar manner (Figs. 5.2). On the other hand, SAPK/JNK was not significantly activated by P. gingivalis LPS and E. coli LPS (Fig. 5.3). Similarly, there was no significant activation of AKT pathway upon stimulation with the two isoforms of P. gingivalis LPS (Figs. S4 A, B and D). In contrast, E. coli LPS significantly induced AKT phosphorylation at 30 min (Figs. S4 C and D). These data demonstrated that the structural heterogeneity of P. gingivalis LPS could determine the activation of signal transduction pathways in HGFs. Hence, penta-acylated P. gingivalis LPS1690 significantly activated NF-κB, p38 MAPK and ERK1/2 signals, but not the

Figure 3. Confocal images showing positive TLR2 (3.1) and TLR4 (3.2) expression, in HGFs, following LPS stimulation. The cells were left untreated (A) or stimulated with P. gingivalis (Pg) LPS1435/1449 (PgLPS1435/1449) (B) PgLPS1690 (C) and E. coli LPS (D) at 1 μg/ml for 6 h. Cells were permeabilized with 0.1% Triton X-100 and subsequently stained with primary antibodies against TLR2, TLR4 and the correspondent secondary antibody labeled Alexa fluor 488 anti-rabbit, and subsequently stained with alexa fluor 555 phalloidin for F-actin. Merged images present the combined TLR2/TLR4, F-actin and nuclear staining (DAPI). Negative control: E. One representative experiment from three independent experiments is shown. Bar = 50 μm.

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### Table 1. List of genes upregulated (fold changes ≥ 1.5; highlighted in bold) and downregulated (fold changes ≤ 0.5; highlighted in italics) by *P. gingivalis* LPS$_{1435/1449}$ and *P. gingivalis* LPS$_{1690}$.

| Genes  | *P. gingivalis* LPS$_{1435/1449}$ | *P. gingivalis* LPS$_{1690}$ |
|---------|---------------------------------|-----------------------------|
| CCL2    | 0.58                            | 3.25                        |
| CXCL10  | 0.21                            | 17.27                       |
| G-CSF   | 0.67                            | 14.91                       |
| GM-CSF  | 0.28                            | 26.77                       |
| IL6     | 0.06                            | 11.93                       |
| IL8     | 0.35                            | 8.64                        |
| HRAS    | 4.66                            | 6.74                        |
| HSPA1A  | 1.28                            | 2.56                        |
| TLR2    | 0.24                            | 1.48                        |
| TLR4    | 2.04                            | 3.14                        |
| CD14    | 0.45                            | 2.26                        |
| IKKB    | 1.73                            | 2.18                        |
| NFKB1   | 1.48                            | 3.55                        |
| NFKBIA  | 0.95                            | 4.25                        |
| MAP2K4  | 1.38                            | 2.55                        |
| MAP3K7P1| 1.61                            | 2.1                         |
| MAP4K4  | 1.37                            | 1.71                        |
| MAPK8   | 1.25                            | 1.99                        |
| IRAK2   | 0.68                            | 2.25                        |

### Discussion

It is evident that LPS as the prototypical endotoxin from gram-negative bacteria is highly potent in inducing innate host response [40]. Over the years, the crucial role of *P. gingivalis* LPS in the pathogenesis of periodontal disease has been intensively investigated [3,4,6,10–19]. Whereas, the exact cell surface receptor for *P. gingivalis* LPS has long been a subject of intense debates, as some studies show the involvement of TLR4, whereas others argue it to be TLR2 [24,41,42]. Similar controversy exists over the major pathway whilst others propose the role of MAPK signal pathway [23,44].

**NF-κB Pathway Played a Crucial Role in *P. gingivalis* LPS$_{1690}$-Induced Expression of IL-6 and IL-8 in HGFs**

Pathway-specific blocking assays further determined the involvement of signal transduction pathways in *P. gingivalis* LPS$_{1690}$-induced IL-6 and IL-8 expression in HGFs. Specific kinase inhibitors were used, including IKK-β inhibitor (IKK-2 inhibitor IV), p38 MAPK (SB202190) and ERK kinase MEK-1 (U0126). The IKK inhibitor significantly attenuated the expression of IL-6 mRNA and protein (Figures 7.3A and 7.4A) as well as IL-8 mRNA and protein (Figs. 7.3B and 7.4B) induced by *P. gingivalis* LPS$_{1690}$ and *E. coli* LPS. The p38 MAPK inhibitor blocked, to a different extent, *P. gingivalis* LPS$_{1690}$- and *E. coli* LPS-stimulated expression of IL-6 and IL-8 (Figs. 7.3 and 7.4). ERK inhibitors did not significantly affect the expression of these cytokines induced by *P. gingivalis* LPS$_{1690}$ while, ERK was significantly involved in *E. coli* LPS-induced expression of IL-6 protein (Fig. 7.4A) as well as IL-8 mRNA and protein (Figs. 7.3B and 7.4B). These data revealed that NF-κB and likely p38 MAPK signaling pathways may play a crucial role in *P. gingivalis* LPS$_{1690}$ induction of pro-inflammatory cytokines, which was different from *E. coli* LPS where NF-κB, p38 MAPK and ERK transduction pathways were, to a different extent, significantly involved in induction of the cytokine expression.

**NF-κB and AKT Pathways.** Similarly, the hexa-acylated *E. coli* LPS activated all aforementioned signaling pathways other than SAPK/JNK. In contrast, tetra-acylated *P. gingivalis* LPS$_{1435/1449}$ predominately activated p38 MAPK and ERK1/2 signals, but did not strongly induce the NF-κB pathway.

### P. gingivalis LPS$_{1690}$ Induced p-p65-NF-κB Nuclear Translocation in HGFs

Nuclear translocation of phospho-NF-κB p65 was observed using confocal immuno-fluorescence microscopy. p-p65-NF-κB translocation was prominent in *P. gingivalis* LPS$_{1690}$-treated cells as compared with both untreated control and *P. gingivalis* LPS$_{1435/1449}$-treated cells (Fig. 6). At the early stage (15 min), p65 was mainly present in the cytoplasm, and the subsequent translocation took place within 60 min following *P. gingivalis* LPS$_{1690}$ stimulation (Figs. 6.1 and 6.2). In the normal condition, p65-NF-κB is retained in the cytosol in an inactive state being complexed with the inhibitory protein IκB. However, upon stimulation with LPS, p-p65-NF-κB translocates to the nucleus following the gradual degradation of IκB. Here we observed that p65-NF-κB was evenly distributed in the cytoplasm in untreated control cells without the sign of p65 immunoreactivity (Fig. 6.1A). However, nuclear expression of p-p65-NF-κB observed in controls after 60 min could be due to the increased intensity with longer exposure time rather than the translocation (Fig. 6.2A). Following the stimulation with *P. gingivalis* LPS$_{1690}$ and *E. coli* LPS for 15 min, p-p65-NF-κB started to migrate to the perinuclear area and the translocation was completed within 60 min (Figs. 6.1C & D and 6.2C & D). These data suggested that *P. gingivalis* LPS$_{1690}$ could induce the nuclear translocation of p-p65 which could be important for the optimal transcription of NF-κB dependent genes.

**Functional Involvement of TLR2 and TLR4 in *P. gingivalis* LPS$_{1690}$-Induced Expression of IL-6 and IL-8**

Blocking assays were used to determine the functional involvement of TLR2 and TLR4 in *P. gingivalis* LPS – HGFs interactions by measuring the expression of downstream cytokines such as, IL-6 and IL-8. We previously demonstrated that *P. gingivalis* LPS$_{1690}$ (not *P. gingivalis* LPS$_{1435/1449}$) and *E. coli* LPS induced significant expression of IL-6 and IL-8 in HGFs [33]. Blockage of TLR4 significantly inhibited the *P. gingivalis* LPS$_{1690}$- and *E. coli* LPS-induced expression of IL-6 and IL-8 mRNAs (Fig. 7.1) and proteins (Fig. 7.2). Whereas, blockage of TLR2 led to significant inhibition of *P. gingivalis* LPS$_{1690}$-induced expression of IL-6 mRNA and protein (Figs. 7.1A and 7.2A), as well as IL-8 mRNA (Fig. 7.1B). It could therefore be assumed that *P. gingivalis* LPS$_{1690}$ may induce the expression of pro-inflammatory cytokines like IL-6 via both TLR2 and TLR4, which may be in a way different from *E. coli* LPS with its hexa-acylated lipid A structure.
4.1

**A**

P. gingivalis LPS Activates TLR4 Signaling in HGFs

![Image of Western Blot Analysis](image)

**B**

E. coli LPS

![Image of Western Blot Analysis](image)

4.2

**A**

P. gingivalis LPS Activates TLR4 Signaling in HGFs

![Image of Western Blot Analysis](image)

**B**

E. coli LPS

![Image of Western Blot Analysis](image)
systemic host responses [44]. Moreover, it has been observed that TLR2 could be an important determinant in response to *P. gingivalis in vivo* [45] and induce inflammatory destruction of bone in mice [46]. In addition, studies using *P. gingivalis* as a whole bacterium have shown CD14-TLR1-TLR2 complex is important to gain access to the cells [47]. Regarding the *in vitro* studies, there is a lack of consistently strong evidence on the cell surface receptors and signal transduction pathways that are involved in the interaction of heterogeneous *P. gingivalis* lipid A structures in host cells such as HGFs [14,24,30,41,42]. The present study attempted to examine the effects of *P. gingivalis* LPS1435/1449 and LPS1690 on the expression of TLR2 and TLR4, downstream signal pathways involved and the expression of pro-inflammatory cytokines in HGFs.

Our present study revealed that LPS containing penta- and hexa-acylated lipid A structures, which were represented by *P. gingivalis* LPS1690 and *E. coli* LPS, upregulated strong expression of TLR4 in HGFs in both dose- and time-dependent manners, although the former also activated the expression of TLR2. On the other hand, tetra-acylated *P. gingivalis* LPS1435/1449 predominantly upregulated the expression of TLR2, and weakly increased the expression of TLR4. These observations were further confirmed by western blot analysis and confocal immuno-fluorescence microscopy. Blocking assays demonstrated that TLR4 was a critical receptor in immuno-inflammatory response to penta-acylated *P. gingivalis* LPS1690 and hexa-acylated *E. coli* LPS. Moreover both forms of LPS activated NF-kB, P38 MAPK and ERK pathways, but not the SAPK/JNK pathway. Additionally, *E. coli* LPS could activate AKT signal. On the contrary, *P. gingivalis* LPS1435/1449 activated to a different extent p38 MAPK and ERK1/2 signals. Taken together, these findings demonstrated that *P. gingivalis* LPS stimulated an overall different expression profile of TLR2 and TLR4 as well as the downstream signaling from that stimulated by the canonical *E. coli* LPS. It has been shown that five of the six fatty acid chains of *E. coli* LPS lipid A could occupy the pocket created by TLR4-MD2 complex that was crucial for TLR4 dimerization and activation of subsequent signaling pathways [40]. As *P. gingivalis* LPS1690 and LPS1435/1449 differentially stimulated the expression profiles of TLR2 and TLR4, the tetra-acylated lipid A structure of the latter might either fill the space available in the pocket or make varied changes to the complex by nullifying the effect of corresponding LPS ligand [40]. Further investigation is required to clarify this point.

Moreover, we also found that *P. gingivalis* LPS1690 induced the nuclear translocation of p-p56, which is critical in the optimal transcription of NF-kB-dependent genes such as IL-6 and IL-8 [48]. Further blocking assays confirmed that NF-kB pathway played a dominant role in induction of IL-6 and IL-8 in HGFs in response to *P. gingivalis* LPS1690 and *E. coli* LPS. These findings could be further discussed in the context of existing literature on the interaction between *P. gingivalis* LPS and host cells. Interaction of *P. gingivalis* LPS with human embryonic kidney cells involves both TLR2 and TLR4, whereas *Salmonella minnesota* LPS is only sensed by TLR4 [28]. Incidentally, later studies reveal that aforementioned *P. gingivalis* LPS could be a mixture of both tetra- and penta-acylated lipid A structures [31]. Hence, the biological activity of penta-acylated lipid A structure of *P. gingivalis* LPS seems to mimic that of canonical hexa-acylated lipid A structure of *E. coli* LPS. It has been demonstrated that penta-acylated lipid A molecules from various Gram-negative bacteria can interact with TLR4, compete and antagonize the action of hexa-acylated *E. coli* LPS [49]. A similar line of observations has been made with heterogeneous lipid A structures of *P. gingivalis* LPS that antagonize the inflammatory response by competing for TLR4 occupation in human umbilical vein endothelial cells (HUVECs) [50]. On the other hand, some studies have shown that TLR2 receptor could be involved in host cell recognition of *P. gingivalis* LPS [28,31,52]. The expression of IL-6 in cementoblasts in response to *P. gingivalis* LPS1690 and *P. gingivalis* LPS1435/1449 is inhibited by blockage of TLR2, but not TLR4 [51]. There is a strong activation of NF-kB pathway in response to *P. gingivalis* LPS1690 with reference to a weak activation of *P. gingivalis* LPS1435/1449, illustrating the significant role of lipid A structure in activation of NF-kB pathway. The host response of dental pulp cells to *P. gingivalis* LPS is also elicited via TLR2/IKK signal transduction axis [53]. Although, it seems that *P. gingivalis* LPS, being different from canonical *E. coli* LPS, may have some propensity to bind TLR2, some have previously argued that it could be due to the contamination of lipoprotein or other components during LPS extraction. However, recent studies demonstrated that highly purified *P. gingivalis* LPS facilitates activation of both TLR2 and TLR4 in various host cell types [28]. In addition, extensively purified *P. gingivalis* LPS stimulates TLR2 expression [23,54,55]. A study has compared the functional effects of highly purified endotoxins from *E. coli*, *P. gingivalis*, *Pseudomonas aeruginosa* and *Bacteroides fragilis* in HUVECs and coronary artery endothelial cells (HCAECs). It shows that HCAECs’ which express TLR2 are responsive to LPS from species other than *E. coli*. It is therefore conceivable that *E. coli* LPS solely utilizes TLR4, whilst LPS from other bacterial species may utilize TLR2 as well [55]. Taking data from foregoing studies and the data derived from the present study into consideration, it shows that although both isoforms of *P. gingivalis* LPS could activate TLR2 expression, *P. gingivalis* LPS1690 is a strong activator of TLR4 expression, whereas *P. gingivalis* LPS1435/1449 is just a weak agonist for TLR4. The hexa-acylated *E. coli* LPS is then a potent agonist for TLR4.

Previous studies have reported that *P. gingivalis* LPS1690 could be a strong inducer for NF-kB pathway through TLR4 signaling in HEK293 cells and endothelial cells [56]. In contrast, *P. gingivalis* LPS1435/1449 does not elicit a significant immuno-inflammatory activity [56,57]. We have recently demonstrated that *P. gingivalis* LPS1690 is an active inducer of pro-inflammatory cytokines in HGFs, whilst *P. gingivalis* LPS1435/1449 is unable to activate the response [33]. Findings of the present study may explain the mechanism behind this observation. Hence, *P. gingivalis* LPS1435/1449 that does not strongly activate TLR4 expression and NF-kB signals is less potent for immuno-stimulation as compared to the more potent isoform of penta-acylated *P. gingivalis* LPS1690, which significantly activates NF-kB pathway similar to that of *E. coli* LPS. This notion may explain the ability of hexa-acylated *E. coli* LPS to induce...
P. gingivalis LPS Activates TLR4 Signaling in HGFs

5.1

5.2

5.3
and penta-acylated \textit{P. gingivalis} LPS$_{1690}$ to induce the NF-$\kappa$B pathway and its downstream pro-inflammatory cytokines in a way different from the tetra-acylated \textit{P. gingivalis} LPS$_{1435/1449}$.

Our study shows that \textit{E. coli} LPS and \textit{P. gingivalis} LPS$_{1690}$, to a different extent induced CD14 expression in HGFs. Although CD14 is known as a receptor for LPS binding, its precise role in \textit{P. gingivalis} LPS-host interaction remains undefined [14,28,36,58]. Some have reported that HGFs do not express membrane-bound CD14 whilst others show the reverse [59,60]. Hence, CD14 may not critically involve in the interaction of HGFs with \textit{P. gingivalis} LPS with reference to toll-like receptors as shown above. The observation that LBP mRNA is significantly upregulated in \textit{E. coli} LPS treated HGFs as compared to cells treated with \textit{P. gingivalis} LPS corroborates the previous finding that the binding capacity of \textit{E. coli} LPS to LBP is much stronger than binding of \textit{P. gingivalis} LPS [23].

Our current findings on structure-function relationship of LPS lipid A component have both biological and clinical implications. Conventionally, it is assumed that hexa-acylated lipid A from canonical \textit{E. coli} LPS is bound to LBP, which is transferred to CD14 and then to TLR4/MD2 complex. This receptor binding subsequently triggers oligomerization and translocation of NF-$\kappa$B into the nucleus, leading to secretion of pro-inflammatory cytokines [61]. However, structural variation of lipid A molecule could bring about different types of biological interaction of LPS with host cells. Previous studies have shown that modification of canonical \textit{E. coli} lipid A structure, by replacing C12 fatty acid (laurate) with long-chain C16 (palmitate), results in less potent LPS.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{\textit{P. gingivalis} (Pg) LPS (PgLPS) and \textit{E. coli} LPS activated the MAPK pathway in HGFs. Kinetics of P38 mitogen activated protein kinase (P38 MAPK), extracellular signal-regulated kinase1/2 (ERK1/2), and Stress-activated protein kinase/c-Jun NH2-terminal kinase (SAPK/JNK) phosphorylation in HGFs are shown in 5.1, 5.2 and 5.3, respectively. Cells were treated with PgLPS$_{1435/1449}$ (A), PgLPS$_{1690}$ (B) and \textit{E. coli} LPS (C) at 1 $\mu$g/mL for the indicated period of time. Cell extracts were prepared and the levels of P38 MAPK, phospho-p38MAPK, ERK, phospho-ERK, JNK and phospho-JNK were determined by western blotting. Quantification of band intensities was performed by densitometry analysis using Image J software. The fold increase values of phospho-proteins of P38 MAPK (5.1D), ERK1/2 (5.2D) and SAPK/JNK (5.3D) as compared with the total protein are shown in the graphs (arbitrary units over control after normalization to the total protein). Equal loading was confirmed by stripping the immunoblot and re-probing it for $\alpha$-Tubulin. The data shown here are from a representative experiment repeated three times with similar results. *Significant difference with a p-value $<$0.05 as compared with the controls without LPS treatment. doi:10.1371/journal.pone.0058496.g005}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Confocal images of p-p65 NF-$\kappa$B nuclear translocation in LPS treated HGFs. The cells were left untreated (A) or stimulated with \textit{P. gingivalis} (Pg) LPS$_{1435/1449}$ (PgLPS$_{1435/1449}$) (B), PgLPS$_{1690}$ (C) and \textit{E. coli} LPS (D) (1 $\mu$g/ml) for 15 min (6.1) and 60 min (6.2), respectively. Cells were permeabilized with 0.1% Triton X-100 and subsequently stained with primary antibodies against anti-phospho-p65 NF-$\kappa$B and the correspondent secondary antibody labeled Alexa fluor 488 anti-rabbit, and subsequently stained with alexa fluor 555 phalloidin for F-Actin. The cytoplasmic p-p65 NF-$\kappa$B appears in green color and F-actin is shown in red color. Negative control: E. The arrow heads show the prominent nuclear staining in the nucleus. Merged 1 images present the combined p-p65 NF-$\kappa$B and F-actin, whereas Merged 2 images show the combined p-p65 NF-$\kappa$B, F-actin and nuclear staining which is counterstained with DAPI. The experiment was performed three times, and the pictures observed correspond to a representative field for each of the times studied. Scale bar = 100 um. doi:10.1371/journal.pone.0058496.g006}
\end{figure}
Figure 7. Blocking assay on the involvement of TLR2/TLR4 and signal transduction pathways in *P. gingivalis* (Pg) LPS$_{1690}$ (PgLPS$_{1690}$) and *E. coli* LPS-induced expression of IL-6 and IL-8 in HGFs. The cells were pretreated for 1 h with anti-TLR2 and anti-TLR4 antibodies in serum free medium, and then treated with PgLPS and *E. coli* LPS at 1 μg/ml for additional 12 h. Total RNA and cell culture supernatants were collected and analyzed for IL-6 (A) and IL-8 (B) by quantitative real-time PCR and ELISA, respectively. The histograms show IL-6 (7.1A) and IL-8 (7.1B) mRNA levels of three independent experiments, and IL-6 (7.2A) and IL-8 (7.2B) protein expression levels of two independent experiments. The results were presented as mean ± SD. Calculation of significant difference were made in comparison to the controls without LPS treatment (p-value...
two independent experiments. The results were presented as mean ± SD. Calculation of significant difference were made in comparison to the controls without LPS treatment (*p-value < 0.05) or the cells treated with LPS alone (##p-value < 0.05). Cells were pretreated with IKK-2 inhibitor IV (IKK-β inhibitor), SB202190 (p38 MAPK inhibitor) and U0126 (ERK inhibitor) in serum free medium for 1 h, then treated with PgLPS and E. coli LPS at 1 μg/ml for additional 12 h. The histograms show IL-6 (7.3A) and IL-8 (7.3B) mRNA levels of three independent experiments, and IL-6 (7.4A) and IL-8 (7.4B) protein expression levels of two independent experiments. The results were presented as mean ± SD. Calculation of significant difference were made in comparison to the controls without LPS treatment (*p-value < 0.05) or the cells treated with LPS alone (##p-value < 0.05).

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Hence, length and number of fatty acid chain could significantly modulate the activation of host signal transduction and the resultant immuno-inflammatory response [43,62,63]. The present study demonstrates that structural heterogeneity in P. gingivalis LPS lipid A is a critical determinant of host cell sensing and signaling towards pathogens. The molecular conformation of lipid A structure has been shown to influence the supra-molecular structure of LPS, i.e. cylindrical lipid A generates lamellar structures whilst conical lipid A forms cubic or hexagonal structures [64,65]. Therefore, three-dimensional arrangement of lipid A is a crucial determinant of LPS activity. As the number of attached fatty acid chains in the lipid A decreases, so does the potency of LPS. E. coli lipid A. So with a conical shape consisting of six asymmetrical acyl chains, E. coli lipid A is a potent activator of immuno-inflammatory response, while P. gingivalis LPS lipid A comprising of four-acyl chains such as, P. gingivalis LPS1435/1449 has strictly cylindrical conformations, which result in relatively weak activity to induce host response. Not only periodontal pathogens like P. gingivalis, but also other Gram-negative bacterial species such as Rhodobacter capsulatus or Chromobacterium violaceum contain tetra-acylated lipid A structures which are weak inducers of pro-inflammatory mediators like IL-6 [66].

Three-dimensional conformation due to variation in lipid A structure could elegantly explain the differential biological activity of P. gingivalis LPS lipid A component, in terms of receptor binding and subsequent activation of signal transduction cascades. For instance, conical shape E. coli LPS bearing hexa-acylated lipid A exclusively binds to TLR4, whereas less conical or more cylindrical PgLPS1690 may interact with TLR2 and/or TLR4. However, P. gingivalis LPS1690 may preferentially bind to TLR4 as five fatty acid chains are sufficient to fully occupy the TLR4 binding pocket as observed previously [40]. In contrast, P. gingivalis LPS1435/1449 which has strictly cylindrical shape with four fatty acid chains, might to some extent occupy TLR2 [67]. However, further investigation is required to confirm these points.

P. gingivalis possesses multiple mechanisms for the binding and uptake of heme into the periplasmic and cytoplasmic compartments. Hemin concentration in the vicinity may transduce conformational changes in P. gingivalis LPS via regulation of hemin receptors or modification of phosphatases [68]. It has also been shown that P. gingivalis grown in high hemin conditions produces predominantly the isoform of LPS with tetra-acylated lipid A structure containing 4-phosphate group, i.e. P. gingivalis LPS1435/1449. In contrast, under low hemin conditions P. gingivalis produces the isoform of LPS with penta-acylated lipid A structure, i.e. P. gingivalis LPS1690 [56]. Hence, certain micro-environmental conditions like high heme concentration during inflammation may promote P. gingivalis to shift its LPS from the predominant penta-acylated lipid A structure towards more tetra-acylated one. This lipid A transformation has been observed in both laboratory and clinical isolates of P. gingivalis [68]. Therefore, it has been suggested that shifting LPS into tetra-acylated lipid A structure may dampen the TLR4-mediated immuno-inflammatory response of gingival tissues, allowing the adaptive pathogen to invade and proliferate in the gingival tissues, thereby leading to progression of periodontal disease. This phenomenon has also been seen in other Gram-negative bacteria such as Yersinia pestis, which modifies its lipid A structure from hexa-acylated to a tetra-acylated lipid A during the transition from 27°C to 37°C [69]. This deacylation process bestows the ability of bacterial LPS to dampen the host immune response. Structural modulation of lipid A in other Gram-negative bacteria such as P. aeruginosa has important clinical implications as well [70].

Within the limitations of the study, the present findings are consistent with other observations [71–73], which demonstrates that the tetra- and penta-acylated lipid A structures of P. gingivalis LPS interact differentially with TLR2 and TLR4, and critically determine the subsequent activation of the downstream signal transduction cascade that differentially modulates immuno-inflammatory response. This reflects the critical importance of lipid A structural heterogeneity of P. gingivalis LPS in activation of TLR receptors and their downstream signal transduction pathways in P. gingivalis-host cell interactions. It could be postulated that the ability to alter the lipid A structure of LPS may be a crucial strategy adopted by P. gingivalis as a keystone periodontal pathogen to evade innate host defense, thereby contributing to periodontal pathogenesis. The present study sheds new light on what is currently known about the interactions of host cells like HGFs with heterogeneous isoforms of P. gingivalis LPS, and contributes to further understanding of the pathogenesis of bacteria-induced inflammatory diseases like periodontal disease, and developing novel preventive and therapeutic approaches to controlling these diseases.

**Experimental Procedures**

**Preparation and Purification of P. gingivalis LPS**

P. gingivalis LPS was isolated from P. gingivalis ATCC 33277 strain using cold MgCl2-ethanol (EtOH) procedure as described previously [28,43]. LPS purification was undertaken using TRI Reagent approach, as documented previously [74]. Crude LPS was subjected to modified Folch extraction to remove phospholipids and further treated to remove trace amounts of endotoxin proteins preparations detected by enhanced Colloidal gold staining [43]. Lipid A was purified using mild acid hydrolysis as described previously, and the total fatty acid content of LPS was analyzed by Gas chromatography (GC) [75]. Extracted lipid A was then analyzed by negative ion MALDI-TOF MS for the structural determination of lipid A observed [28,43]. Two detected ion peaks that were clustered around a mass of 1690 and 1435/1449 designated as penta-acylated P. gingivalis LPS1690 and tetra acylated P. gingivalis LPS1435/1449, respectively. Highly purified E. coli LPS (JM 83 wild type strain) served as positive control.

**HGF Cell Culture**

Primary HGFs were purchased from Sciencell research laboratories (Carlsbad, CA, USA) and cultured according to the manufacturer’s instructions. Cells were suspended in fibroblast medium consisting of the basal medium, 2% Fetal Bovine Serum (FBS), fibroblast growth supplement (FGS) and 2% penicillin/streptomycin (P/S), and then incubated with an atmosphere of 5% CO2 and 95% air at 37°C [33,76]. The cultured cells at 3–4 passages, with spindle shaped morphology, were designated as appropriate for the following experiments.
**LPS Stimulation**

HGFs were cultured in six-well plates with $1 \times 10^5$ cells per well. While reaching 95% confluence, FM medium was replaced with act-FM for subsequent dose- and time-dependent experiments. In the dose-dependent assay, cells were stimulated with *P. gingivalis* LPS$_{1435/1449}$, *P. gingivalis* LPS$_{1690}$ or *E. coli* LPS at various doses (1 ng/ml–10 μg/ml). Based on the results, 1 μg/ml was selected as the appropriate dose for the subsequent time-dependent experiments. In the time-dependent assays, cells were treated with 1 μg/ml of *P. gingivalis* LPS or *E. coli* LPS and incubated for different period of time (2–48 h). Cells without LPS treatment were taken as the controls. Culture supernatants were collected and centrifuged to remove the cell debris and stored in -70°C until further use. The attached cells were then washed with PBS and subjected to RNA and protein extraction, respectively. Total proteins were extracted by using Mammalian protein extraction buffer plus protease and phosphatase inhibitors (Pierce, Thermo Scientific, USA). Cell lysates were collected and centrifuged at 14,000 rpm for 4°C for 15 min to remove the cell debris. The protein concentration was then measured in both cellular proteins and culture supernatants using BCA protein assay kit (Pierce, Thermo scientific, USA).

**Transcriptomic Analysis of TLR Signaling Pathway using PCR-array**

In order to explore the holistic view of gene expression in HGFs, upon treatment with *P. gingivalis* LPS$_{1435/1449}$ and LPS$_{1690}$, a panel of 84 genes related to TLR signaling pathway was examined using RT$^2$ profiler PCR arrays (PAHS 018C, SA biosciences, Frederick, MD, USA). The complete description of the analyzed genes was listed in Table S2. In order to ensure the high quality of cDNA, reverse transcription reactions were performed using RT$^2$ First Strand Kit according to the manufacturer’s protocol (SuperArray, Frederick, MD, USA). Diluted cDNA template was mixed with RT$^2$ qPCR Master Mix (SYBR Green/Rox, SA Biosciences) and RNase-free water (SuperArray Bioscience Corp, Frederick, MD, USA). Then 25 μL of the experimental cocktail were aliquoted to each well of the 96-format PCR array plate containing pre-dispensed gene specific primers. Finally, mRNA was amplified on a StepOne Real-Time PCR system (ABI, Foster City, CA, USA), using the following amplification procedure. After the initial incubation at 95°C for 10 min, 40 cycles of amplification was accomplished with 15 s at 95°C for denaturation and 1 min at 60°C for annealing, respectively. To check the differential expression of related genes, each run was performed in duplicates with reference to the controls. To ensure the reliability, reverse transcription controls (RTC), positive controls (PPC) and genomic DNA controls (GDC) were included in the experiments. The instrument’s software calculated the threshold cycle (Ct) values for all genes tested in the array. Finally, the fold changes in gene expression were calculated for pairwise comparison using the ΔΔCt method from the raw threshold cycle data 2010 [77]. Gene expression was considered up-regulated (fold-changes $>1.5$) or down-regulated (fold-changes $<0.5$), and the analysis was carried out using the SA biosciences web-based PCR array data analysis software (SA Biosciences, Frederick, MD, USA).

**Evaluation of Candidate Genes by Real-time qPCR**

Real-time qPCR was performed to further examine the candidate genes related to TLR pathway. Total RNA extraction, cDNA synthesis and RT-PCR reaction were performed as mentioned previously [33]. Total RNA was extracted by using RNeasy mini kit (Qiagen, USA) and the RNA concentration was quantified by using the NanoDrop spectrophotometer (Thermo, USA). The extracted RNA was then subjected to cDNA synthesis by using reverse transcriptase-PCR described elsewhere [26]. Q-RT-PCR was performed in StepOne Real-Time PCR System (Applied Biosystems, USA) in at least three separate experiments. Amplification reactions were performed in a final volume of 20 μl containing 10 μl of Power SYBR Green PCR MasterMix (Applied Biosystems), 1 μl of cDNA template and 1 μl of each pairs of primers (Sigma). Real-time primer pairs were designed using primer 3 software (NCBI, USA) (Table S3). The amplification efficiencies of the primers used were above 90%. Real-time qPCR reaction conditions were set at 95°C for 10 min followed by 40 cycles at 95°C for 15 s and 60°C for 1 min. The expression level of each gene was normalized to a β-actin (Ct) and fold-changes for each gene were calculated by comparing the LPS-treated test and untreated controls from the Ct values according to the Ct approach [26,33].

**Detection of TLRs Expression by Confocal Immunofluorescence Microscopy**

HGFs were seeded on 12 mm circular cover slips in six-well plates ($1 \times 10^5$ cells/well) and cultured overnight in order to achieve over 80% confluence. Afterwards, cells were incubated with 1 μg/ml of either *P. gingivalis* LPS$_{1435/1449}$, *P. gingivalis* LPS$_{1690}$ or *E. coli* LPS for 6 h and 24 h. Cells without any stimulus were taken as controls. After LPS stimulation, cover slips were washed twice in PBS and fixed with 4% (V/V) paraformaldehyde in PBS for 15 min at room temperature. The cover slips were then washed three times in PBS, and permeabilized by treatment with 0.1% Triton X-100 in PBS for 10 min. Following washing three times in PBS, and blocked with PBS containing 3% bovine serum albumin (BSA), plus Tween 20 (0.1% v/v), blocking buffer for 30 min at room temperature, cells were then incubated overnight at 4°C with blocking buffer containing the primary antibodies for TLR4 (polyclonal anti-rabbit TLR4 antibody, 1:100, Santa Cruz Biotechnology, Santa Cruz, CA, USA) and TLR2 (monoclonal mouse anti-human TLR2 antibody, 1:100, Abcam). Cells were then washed with 0.1% BSA-PBS and incubated in blocking buffer containing corresponding secondary antibodies (anti-rabbit or anti-mouse IgG conjugated with Alexa fluor 488, 1:200) for 1 h at room temperature, and excess stain was rinsed off by PBS washes. The cell contour stained for F-actin was detected after 20 min incubation by phalloidin conjugated Alexa fluor 555 (1:40, Invitrogen, Eugene, Oregon, USA). Next, cells were washed with PBS/TBS and visualized on a confocal laser-scanning microscope (Olympus Fluoview FV 1000; Olympus, Tokyo, Japan) using FV10-ASW 3.0 software for image analysis. For detection of cell nuclei, cells were stained with DAPI (4’6-diamidino-2- phenylindole, dilactate, Invitrogen, USA). Cells treated with IgG isotype control (R & D systems) instead of the primary antibody served as the negative control.

**Pathway-focused Western Blot Analysis**

Western blot analysis was performed to examine the expression of TLR2, TLR4 and other key molecules related to major signal transduction pathways such as p-IκBζ, p-p65, p-p38 MAPK, p-ERK, p-JNK and p-AKT. HGFs were serum starved for 24 h and then stimulated with 1 μg/ml of *P. gingivalis* LPS$_{1435/1449}$, *P. gingivalis* LPS$_{1690}$ or *E. coli* LPS, for 5, 15, 30, 60 and 120 min. Western blots were performed according to the standard protocol, which were used in previous studies [78]. All the pathway molecules were examined using repeated stripping technique for each blot, in order to minimize the batch-to-batch variation. Initially, each blot was probed for phosphorylated proteins, followed by stripping and re-probing with the appropriate probe.
for total proteins. α-Tubulin was used as the internal loading control. In brief, 40 μg of protein lysates were separated by 10% SDS-PAGE and transferred onto PVDF (Polyvinylidene difluoride) membranes (Roche, USA) by using the Mini-PROTEAN Tetra electrophoresis system and the Mini Trans-Blot transfer system (Bio-Rad, USA). Following the transfer, blots were blocked with protein-free T20 (TBS) blocking buffer (Thermo scientific, USA) at room temperature for 1 h and incubated with primary antibody at 4°C while shaking overnight. Primary antibodies were all obtained against monoclonal rabbit anti-human antibodies; TLR4 antibody (1:1000, Santa Cruz), TLR2 antibody (1:1000, Cell Signaling), phospho IκBα (1:1000, Cell Signaling), IκBα antibody (1:1000, Cell Signaling), phospho NF-κB p65 (1:1000, Cell Signaling), NF-κB p65 (1:1000, Cell Signaling), phospho-p38 antibody (pP38MAPK) (1:1000, Cell Signaling), phospho-IκBα antibody (1:1000, Cell Signaling), phospho-SAPK/JNK p-JNK antibody (1:1000, Cell Signaling), SAPK/JNK antibody (1:1000, Cell Signaling), phospho-ERK1/2 antibody (1:2000, Cell Signaling), ERK1/2 antibody (1:1000, Cell Signaling), phospho-AKT antibody (1:1000, Cell Signaling), and AKT antibody (1:1000, Cell Signaling). α-Tubulin (1:2000, Cell Signaling) was used as the internal loading control. After being washed with the washing buffer, the blots were incubated with horseardish peroxidase (HRP) conjugated goat-anti-rabbit IgG (1:10000, Cell Signaling) over night at 4°C. Bound immune-complexes were detected using ECL reagent (1:10000, Cell Signaling) at room temperature for 1 h, then the bound immune-complexes were detected using ECL reagent (super signal west pico chemiluminescent kit, Thermo Scientific, USA). Detected bands were scanned on a calibrated densitometer (GS-800, Bio-Rad, Hercules, CA, USA) and the integrated density of each band was quantified using Image J software-based analysis (http://rsb.info.nih.gov/ij/).

Analysis of NF-κB Nuclear Translocation

Activation and translocation of NF-κB were observed by confocal immunofluorescence assay as mentioned previously. After LPS stimulation for 15 and 60 min, cells were fixed, blocked and incubated with rabbit anti-phospho NF-κB p65 (1:100, Cell Signaling) over night at 4°C. After three washes in 0.1% BSA-PBS, the cells were incubated with FITC conjugated goat anti-rabbit secondary antibody at room temperature for 60 min. After rinsing in PBS, cells were counterstained with DAPI (10 μg/ml) for 5 min. The slides were then washed, air-dried and mounted with fluorescent mounting medium and visualized on a confocal laser-scanning microscope (Olympus Fluoview FV 1000; Olympus, Tokyo, Japan) using FV10-ASW 3.0 software for image analysis. Negative controls were established by omitting primary antibody.

Blocking Assays of Signal Transduction Pathways

Neutralization of TRGs was achieved by using TRG-specific blocking antibodies. HGFs were grown in six-well tissue culture plates until 90% confluent as described above. Then the cells were incubated for 1 h with serum free fresh media containing 20 μg/ml of anti-human TLR2 antibody (eBioscience, San Diego, USA) and 20 μg/ml of anti-human TLR4 antibody (eBioscience) using 20 μg/ml of mouse IgG2a, isotype control (Biologend, San Diego, CA, USA) as the negative control, prior to the addition of LPS. Afterwards, cells were challenged with 1 μg/ml of either P. gingivalis LPS1690, P. gingivalis LPS1435/1449, or E. coli LPS for 12 h. Cells incubated with medium alone was considered as the negative control, while cells incubated with LPS without prior incubation with TRL antibody were used as the positive control. After stimulation, culture media supernatants were collected for cytokine assays and the cells were harvested for extraction of total mRNA.

Statistical Analysis

All experiments were repeated in at least three assays for real-time qPCR, western blot and two assays for ELISA. All values were presented as the mean ± SD. The statistical significance of difference between the data sets from the dose-dependent assay was evaluated by student t-test, one-way analysis of variance (ANOVA) and post-hoc testing with Bonferroni and LSD methods, as appropriate. Additionally, repeated measures ANOVA were used to determine the differences between data sets from the time-dependent assay. A p-value < 0.05 was considered statistically significant. All statistical analysis was performed using a software program (SPSS 19.0, SPSS Inc, Chicago, IL, USA).

Supporting Information

Figure S1 Confocal images of TLR2 (S1.1) and TLR4 (S1.2) expression in HGFs following LPS stimulation for 24 h. HGFs were left untreated (A) or stimulated with 1 μg/ml of P. gingivalis (Pg) LPS1435/1449 (PgLPS1435/1449) (B) PgLPS1690 (C) and E. coli LPS (D). Negative control: E. Cells were then permeabilized with 0.1% Triton X-100 and subsequently stained with primary antibodies against TLR2, TLR4 and the correspondent secondary antibody labeled Alexa fluor 488 anti-rabbit, and subsequently stained with alexa fluor 555 phalloidin for F-actin. All experiments were repeated in at least three independent experiments is shown. Bar = 50 μm or 100 μm. (TIF)

Figure S2 P. gingivalis (Pg) LPS -induced gene expression of inflammatory mediators in HGFs. The cells were treated with PgLPS at 1 μg/mL or culture medium alone for 24 h.
Figure S3 *P. gingivalis* (Pg) LPS1690 induced the mRNA expression of inflammatory mediators in HGFs. The cells were stimulated with PgLPS and *E. coli* LPS (1 μg/mL) for 24 h. The harvested RNA was subjected to real-time quantitative PCR analysis. Fold increase of genes were analyzed relative to the internal control β-Actin, including GM-CSF (A), CXCL10 (B), IL-6 (C) and IL-8 (D). Each bar represents the mean±SD of three independent experiments with three replicates. *Significant difference with a p-value <0.05 as compared with the controls without LPS treatment.

(TIF)

Figure S4 Kinetics of protein kinase B (PKB) or AKT phosphorylation in HGFs. The cells were stimulated with *P. gingivalis* (Pg) LPS1435/1449 (PgLPS1435/1449) (A), PgLPS1690 (B) and *E. coli* LPS (C) at 1 μg/mL for the indicated periods of time. Cell extracts were prepared and the sample aliquots containing 40 μg of protein were separated by SDS-polyacrylamide gel electrophoresis and immunoblotted with anti-phospho AKT specific antibodies. Fold increase values of p-AKT optical density (arbitrary units) from triplicate samples. Representative heat maps showing the fold-changes of each gene in PgLPS1435 (A)- and PgLPS1690 (B) -treated HGFs with reference to the controls. Genes that were upregulated over 2 folds are marked in red color and those down regulated by 0.5 folds are shown in green color.

(DOCX)

Table S2 Genes included in the TLR signaling pathway RT-PCR array kit (SA Biosciences). A total of 84 genes related to TLR signaling family were analyzed, including adaptor and effector proteins, members of the NF-κB, JNK/p38, IRF and JAK/STAT signaling pathways as well as downstream pathway genes.

(DOCX)

Table S3 Nucleotide sequence of primers for real-time PCR.

Author Contributions

Conceived and designed the experiments: TDKH CJS LJJ. Performed the experiments: TDKH CJS. Analyzed the data: TDKH CJS LJJ. Contributed reagents/materials/analysis tools: RPD CYW YW LJJ. Wrote the manuscript. This study received the Southeast Asian Division of the International Association for Dental Research (IADR-SEA) Unilever/Hatton Divisional Award in 2011.

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References

1. Pihlerov RL, Michalowicz BS, Johnson NW (2005) Periodontal diseases. Lancet 366: 1809-1820.
2. Socransky SS, Haiffige AD (1992) The bacterial etiology of destructive periodontal disease: current concepts. J Periodontol 63: 322-331.
3. Darveau RP (2010) Periodontic: a polymicrobial disruption of host homeostasis. Nat Rev Microbiol 8: 481-490.
4. Hajiengallga G (2009) Porphyromonas gingivalis-host interactions: open war or intelligent guerrilla tactics? Microbes Infect 11: 637-645.
5. Schwartz J, Simons FL, Parker RB (1972) The passage of tritiated bacterial endotoxin across intact gingival crevicular epithelium. J Periodontol 43: 270-276.
6. Curtis MA, Zenobia C, Darveau RP (2011) The relationship of the oral microbiota to periodontal health and disease. Cell Microbe 10: 302-306.
7. Brencher E, Rietsema ET (2005) Innate immune sensing and its roots: the story of endotoxin. Nat Rev Immunol 3: 169-176.
8. Rietschel ET, Brade H (1992) Bacterial endotoxins. Sci Am 267: 54-61.
9. Rietschel ET, Kirke T, Schade FU, Mamat U, Schmidt G, et al. (1994) Bacterial endotoxin: molecular relationships of structure to activity and function. FASEB J 8: 217-225.
10. Dixon DR, Darveau RP (2005) Lipopolysaccharide heterogeneity: innate host responses to bacterial modification of lipid a structure. J Dent Res 84: 584-595.
11. Grenier D, Mayrand D (1987) Functional characterization of extracellular vesicles produced by Bacteroides gingivalis. Infect Immun 55: 111-117.
12. Ubara A, Takada H (2007) Functional TLRs and NODs in human gingival fibroblasts. J Dent Res 86: 249-254.
13. Tamura M, Tokuda M, Nagaoka S, Takada H (1992) Lipopolysaccharides of Bacteroides intermedius (Prevotella intermedia) and Bacteroides (Porphyromonas) gingivalis induce interleukin-8 gene expression in human gingival fibroblast cultures. Infect Immun 60: 4932-4937.

14. Tatsuki K, Yamazaki K, Akashi S, Minek K, Kamada H, et al. (2000) Toll-like receptors confer responsiveness to lipopolysaccharide from Porphyromonas gingivalis in human gingival fibroblasts. Infect Immun 68: 3731-3735.
15. Aza T, Kurata K, Hirai K, Uchihashi T, Uematsu T, et al. (2009) Human gingival fibroblasts are critical in sustaining inflammation in periodontal disease. J Periodontol Res 44: 21-27.
16. Koogula L, Ellhain K, Tenenbaum H, Werner S (2009) Variable cell responses to *P. gingivalis* lipopolysaccharide. J Dent Res 88: 741-745.
17. Diva Z, Lii C, Zheng L, Zhiyuan G, Jie Y (2008) Lipopolysaccharide (LPS) of Porphyromonas gingivalis induces IL-1beta, TNF-alpha and IL-6 production by THP-1 cells in a way different from that of Escherichia coli LPS. Infect Immun 14: 99-107.
18. Darveau RP, Belton CM, Reife RA, Lamont RJ (1998) Local chemokine paralysis, a novel pathogenic mechanism for Porphyromonas gingivalis. Infect Immun 66: 1690-1693.
19. Reife RA, Shapiro RA, Bamber BA, Berry KK, Mick GE, et al. (1995) Porphyromonas gingivalis lipopolysaccharide is poorly recognized by molecular components of innate host defense in a mouse model of early inflammation. Infect Immun 63: 4686-4694.
20. Heumann D, Roger T (2002) Initial responses to endotoxins and Gram-negative bacteria. Clin Chim Acta 325: 59-72.
21. Triantafilo M, Triantfilo K (2002) Lipopolysaccharide recognition: CD14, TLRs and the LPS-activation cluster. Trends Immunol 23: 301-304.
22. Lee HK, Lee J, Tobias PS (2002) Two lipoproteins extracted from Escherichia coli K-12 LPS25 lipopolysaccharide are the major components responsible for Toll-like receptor 2-mediated signaling. J Immunol 168: 4012-4017.
23. Hirschfeld M, Weis J, Tschuchakov V, Salkowski CA, Coby MJ, et al. (2001) Signaling by toll-like receptor 4 and 2 agonists results in differential gene expression in murine macrophages. Infect Immun 69: 1477-1482.

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46. Gibson FC, 3rd, Genco CA (2007) Porphyromonas gingivalis mediated
45. Burns E, Eliyahu T, Uematsu S, Akira S, Nussbaum G (2010) TLR2-dependent
44. Liu R, Desta T, Raptis M, Darveau RP, Graves DT (2008) P. gingivalis and E.
43. Berezow AB, Ernst RK, Coats SR, Braham PH, Karimi-Naser LM, et al. (2009)
37. Sugawara S, Sugiyama A, Nemoto E, Rikiishi H, Takada H (1998)
32. Chen C, Coats SR, Bumgarner RE, Darveau RP (2007) Hierarchical gene
31. Reife RA, Coats SR, Al-Qutub M, Dixon DM, Braham PA, et al. (2006)
29. Darveau RP, Arbabi S, Garcia I, Bainbridge B, Maier RV (2002)
28. Darveau RP, Pham TT, Lemley K, Reife RA, Bainbridge BW, et al. (2004)
25. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2002) Counteracting
24. Martin M, Katz J, Vogel SN, Michalek SM (2001) Differential induction of
23. Hajjar AM, Ernst RK, Tsai JH, Wilson CB, Miller SI (2002) Human Toll-like
22. Hajishengallis G, Nisonoff A, Genco RJ (2003) Heterogeneous expression of Toll-like
21. Hajishengallis G, Martin M, Shaffer J, Genco RJ (2003) Toll-like receptor 2 is
downregulated by Porphyromonas gingivalis in human gingival fibroblasts.
20. Hajishengallis G, Martin M, Shaffer J, Genco RJ (2003) Differential expression of
19. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) toll-like receptors
18. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) The role of Toll-like
17. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
16. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
15. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
14. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
13. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
12. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
11. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
10. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
9. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
8. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
7. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
6. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
5. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
4. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
3. Medrano-Abrego N, Genco RJ, Hajishengallis G (2005) Porphyromonas gingivalis
2. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
1. Hajishengallis G, Martin M, Schifferle RE, Genco RJ (2003) Porphyromonas gingivalis
glycosyl phosphate present in the “isolated lipid A” fragment of the Bordetella pertussis endotoxin. Carbohydr Res 175: 273–282.

76. Di Domenico G, Del Vecchio L, Postiglione L, Ramaglia L. (2003) Immunophenotypic analysis of human gingival fibroblasts and its regulation by Granulocyte-Macrophage Colony-Stimulating Factor (GM-CSF). Minerva Stomatol 52: 81–87, 87–91.

77. Baluchamy S, Zhang Y, Ravichandran P, Ramesh V, Sodipe A, et al. (2010) Differential oxidative stress gene expression profile in mouse brain after proton exposure. In Vitro Cell Dev Biol Anim 46: 718–725.

78. Ardeshna KM, Pizzey AR, Devereux S, Khwaja A. (2000) The PI3 kinase, p38 SAP kinase, and NF-κB signal transduction pathways are involved in the survival and maturation of lipopolysaccharide-stimulated human monocyte-derived dendritic cells. Blood 96: 1039–1046.