Effects of Porphyromonas gingivalis and Escherichia coli Lipopolysaccharides on Mononuclear Phagocytes

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The mononuclear phagocyte plays an important role in the regulation of microbe-induced inflammation, in part through its ability to secrete mediators, particularly cytokines, in response to microorganisms and their products. To evaluate the effects of the microbial flora associated with chronic adult periodontitis on cytokine induction, lipopolysaccharide (LPS) from the periodontopathogen Porphyromonas gingivalis was used to stimulate naïve and phorbol ester-primed U937 mononuclear cells, as well as elutriated human peripheral blood monocytes. We assessed the effect of this LPS, in comparison to that of LPS from Escherichia coli, on cell proliferation, cytokine induction, and surface expression of the LPS receptor CD14. P. gingivalis LPS stimulated proliferation of U937 cells at concentrations of greater than 1 ng/ml, while E. coli LPS inhibited proliferation. Phorbol myristic acid (PMA)-treated U937 cells and elutriated monocytes responded to E. coli LPS activation by producing tumor necrosis factor alpha (TNF-α) mRNA and protein; however, P. gingivalis LPS induced greater numbers of TNF-α mRNA-positive cells and higher (P < 0.05) levels of protein than did E. coli LPS. Both cell types expressed interleukin-1 beta (IL-1β) mRNA and protein in response to either LPS treatment. Compared with E. coli LPS, P. gingivalis LPS induced significantly (P < 0.05) higher numbers of IL-1 mRNA-positive U937 cells and elutriated monocytes, as well as production of significantly more (P < 0.05) IL-1 protein by the monocytes. The PMA-treated U937 cells and the monocytes produced high levels of IL-1 receptor antagonist mRNA and protein which were only marginally affected by the LPS preparations. While E. coli LPS induced expression of CD14 on the surface of PMA-primed U937 cells and monocytes, P. gingivalis LPS exhibited a significantly (P < 0.05) greater ability to enhance receptor levels. Our results indicate that P. gingivalis LPS can activate the mononuclear phagocyte for proliferation, cytokine production, and CD14 expression, providing evidence for the potential of this bacterial component to act as a critical regulatory factor in the chronic inflammatory response associated with periodontitis.

The mononuclear phagocyte is one of the principal cell types involved in the inflammatory response which occurs under conditions of chronic infection (40). Periodontitis is an infectious process characterized by chronic inflammation affecting the supporting structures of the teeth. If left untreated, it may eventually lead to total destruction of the connective tissue and alveolar bone (39). Specific gram-negative anaerobic bacteria, such as Porphyromonas gingivalis, have been suggested to play a primary role in the initiation and exacerbation of this condition (21). Moreover, the host response to the periodontal microbial flora has been implicated in the pathology of periodontitis (27, 29). The immune cells present in the periodontium, which could contribute to local host responses, include T, B, and phagocytic cells.

Lipopolysaccharide (LPS) is a major component of the outer membrane of gram-negative bacteria, including that of P. gingivalis (34), and has the ability to activate host cells, especially mononuclear phagocytes (24). This activation is mediated by the binding of LPS to cell surface receptors, e.g., the LPS receptor CD14 (18, 36). Host responses can also be regulated by cytokines produced by several cell types in response to stimulation with LPS. In this regard, the macrophage plays an important role in regulating local inflammatory responses to bacterial insult by the production of cytokines, particularly proinflammatory interleukin-1 beta (IL-1β) and tumor necrosis factor alpha (TNF-α) and the anti-inflammatory IL-1 receptor antagonist (IL-1ra) (2, 8, 9).

LPS from the periodontopathogen P. gingivalis differs biochemically from classical LPS derived from Escherichia coli (12). The differences involve variations in phosphorylation and acylation patterns in the biologically active component, lipid A, and relative decreased toxicity of P. gingivalis LPS compared with E. coli LPS in lethal endotoxemia animal models (25, 28). Furthermore, studies have shown that, in contrast to E. coli LPS, P. gingivalis LPS is capable of inducing some immune responses in the LPS-hyporesponsive C3H/HeJ inbred mouse strain (12, 20). Mechanisms underlying the toxic and immunomodulating effects of Porphyromonas LPS in vivo are not well understood.

To determine the contribution of P. gingivalis LPS to chronic inflammatory periodontal disease, this study was aimed at testing the hypothesis that P. gingivalis LPS is functionally different from E. coli LPS in its ability to activate the mononuclear phagocyte. Therefore, we examined the effects of E. coli and P. gingivalis LPSs on proliferative responses, cytokine mRNA and protein induction, and LPS receptor expression in the U937 monocytic cell line and elutriated human peripheral blood monocytes. Our studies demonstrate that LPS from the periodontopathogen P. gingivalis, compared to E. coli LPS, displays an enhanced ability to induce monocyte proliferation and cytokine expression which may be related to increased expression of membrane CD14.

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MATERIALS AND METHODS
Reagents. LPS from *P. gingivalis* ATCC 33277 was prepared by hot phenol extraction (23). LPS from *E. coli* K235 was prepared by phenol-water extraction (22). No protein was detected in the LPS preparations by spectrophotometric methods, by silver staining of samples resolved in polyacrylamide gels, or by silver stained gels reprobed electrophoretically resolved in a polyacrylamide gel, electroblotted onto a nitrocellulose membrane, and stained with a solution of colloidal gold (Enhanced Colloidal Gold Total Protein Detection Kit; Bio-Rad Laboratories, Hercules, Calif.). Stock solutions of LPS were prepared (1 mg/ml in pyrogen-free water) and stored at 4°C. Aliquots were prepared before use or stored at −70°C. The modified Eagle medium (DMEM) and RPMI 1640 medium (Cellgro; Mediatech, Washington, D.C.), fetal calf serum (FCS; Hyclone Labs, Logan, Utah), phosphate-buffered saline (PBS; 9.25 mM NaHPO₄, 5.25 mM NaH₂PO₄, 145 mM NaCl, 145 mM KH₂PO₄), and elutriation components contained less than 0.3 ng of endotoxin per ml as measured by a chromogenic Limulus amebocyte lysate assay (Whittaker Bioproducts, Inc., Walkersville, Md.).

Preparation of U937 cells and elutriated monocytes. The well-characterized U937 cell line (35) was maintained at 37°C in an atmosphere of 5% CO₂ in air. Monocytes were cultured in 48-well flat-bottom tissue culture plates (Falcon) in triplicate at 10⁶ cells per well in complete medium. Cultures were incubated (37°C, 5% CO₂) for 10 h, nonadherent cells were harvested by centrifugation at 400 × g, and adherent cells were harvested according to the procedures described above, in complete medium in 25-cm² flasks at 10⁶ cells/ml. Following adherence of cells, an equal volume of DMEM supplemented with 10% FCS was added per well, and the plates were incubated for 1 h at room temperature. Supernatants (undiluted or diluted 1:1, 2:1, or 4:1) or cytokine standards (R&D Systems; see below) were added, and the mixture was incubated at 37°C for 16 h. The plates were washed five times with 10 ml of PBS, pH 7.0, containing 100 µg of DNase per ml, 250 µg of gentamicin per ml, and 2 µl of heparin per ml and then prepared for hybridization as described above. Each dilution of standards was applied at least four times as a triplicate. The stimulated U937 cells and elutriated monocytes were cultured as described above, in complete medium in 25-cm² flasks at 10⁶ cells/ml. Following treatment, nonadherent cells were harvested by centrifugation at 400 × g for 10 min at room temperature (non-PMATreated U937 cells) and adherent cells were harvested by gentle scraping. Cytospin preparations of treated cells were fixed in 3% paraformaldehyde for 1 h, acetylated with 0.25% acetic anhydride-triethanolamine for 15 min, and prehybridized with a solution of 50% formamide, 1 × SSC (150 mM NaCl, 15 mM Na citrate). Denhardt’s solution, 0.05% trypsin DNA, 0.025% yeast RNA, and 10% dextran sulfate for 3 h. The cells were then hybridized with 15 µl of hybridization buffer containing a heat-denatured riboprobe for the cytokine of interest. The unhybridized riboprobe was removed by a 45-min incubation with 20 µg of RNAse A per ml in STE buffer (500 mM NaCl, 20 mM Tris-HCl, 1 mM EDTA) and high-stringency washing with 2 × SSC–50% formamide at 30°C (three times) and with 0.5 × SSC at 25°C (twice).

Cells positive for cytokine mRNA were detected with an alkaline phosphatase-conjugated antidigoxigenin antibody (Boehringer GmbH) diluted 1:500 in 1% normal horse serum. The presence of antibody was detected by color development after the addition of a nitroblue tetrazolium substrate (Boehringer GmbH). Cells detected with digoxigenin-labeled RNA probes were quantitated with bright-field microscopy by direct counting. Five fields of positive and negative cells were counted at a magnification of ×10, and the values were expressed as the number of positive cells per 100 cells counted.

Flow cytometry analysis for CD41. Stimulated U937 cells and elutriated monocytes were cultured as described above and then characterized for the human LPS receptor CD14 by use of mouse monoclonal antibody MY4 (Coulter Clone, Hialeah, Fla.). The cells were harvested by gentle scraping and phenotypically characterized following incubation of aliquots of cell preparations with either monoclonal antibody MY4 (Coulter Clone, Hialeah, Fla.) or the immunoglobulin G2b isotype-control monoclonal antibody (Coulter Clone, Hialeah, Fla.). The aliqouts with a greater than 95% monocyte profile were pooled and counted. Monocytes (10⁶/ml) were cultured in 48-well tissue culture plates (500 µl/well) or 25-cm² tissue culture flask (5 ml/flask; Falcon; Becton Dickinson & Co., Lincoln Park, N.J.) in serum-free DMEM for 2 h at 37°C in 5% CO₂ in air. Following adherence of cells, an equal volume of DMEM supplemented with heat-inactivated FCS, glutamine, penicillin, and streptomycin was added to each culture to yield final supplemental concentrations of 10% FCS, 2 mM l-glutamine, 100 U of penicillin per ml, and 100 U of streptomycin per ml (complete DMEM). The cells were kept in culture for 24 h prior to use in the experimental protocol.

Proliferation of U937 cells. U937 cells were cultured in 96-well flat-bottom tissue culture plates (Falcon) in quadruplicate at 10⁳ cells per well in complete RPMI medium. The cells were incubated (37°C, 5% CO₂ alone or with the concentrations of LPS indicated, and the proliferative responses of the monocyte cells are expressed as a proliferation index (PI) calculated as follows: PI = (E – C)/C, where the PI is the mean level of [3H]TDR uptake by the cytokine treated control cultures, which contained no LPS, divided by the control [3H]TDR uptake. Statistical analysis. A comparison of the significance of the effects of LPS on cytokine and CD14 induction in U937 cells and monocytes was made with Student’s t test and Fisher’s PLSD statistical methods by using Statview 4.5 software (Abacus Concepts, Berkeley, Calif.) on a PowerMac 8500 computer (Apple Computer, Inc., Cupertino, Calif.).
96 h. Addition of PMA to U937 cultures for the initial 48 h of culture resulted in adherence of the cells (64% ± 10%) and a marked reduction in proliferation ([3H]TdR uptake, 2,100 cpm) with a PI = 0.88.

TNF-α production. In the absence of PMA differentiation, control U937 cells did not produce any detectable TNF-α (data not shown). Although detectable levels of TNF-α were present in supernatants of PMA-induced U937 cells, significantly (P < 0.05) larger amounts of TNF-α were released within 4 h after PMA-treated U937 cells were stimulated with either LPS preparation (Fig. 2). P. gingivalis LPS stimulated the greatest release of TNF. Low doses of P. gingivalis LPS had very little effect on the PMA-differentiated U937 cells, while larger amounts of P. gingivalis LPS induced a dose-response induction of TNF-α (Fig. 3). The ability of E. coli LPS to induce TNF-α production reached a plateau at a dose of 10 ng/ml.

The elutriated human monocytes stimulated with either LPS preparation produced significantly (P < 0.05) more TNF-α than did control cultures by 24 h (Fig. 4A). Monocytes treated with 0.1 and 5 μg of P. gingivalis LPS per ml produced significantly (P < 0.05) higher levels of TNF than did cells treated with the same concentrations of E. coli LPS.

IL-1β production. Undifferentiated U937 cells produced no detectable IL-1β following either LPS treatment, or the kinetics of IL-1β production by PMA-activated cells stimulated with LPS differed from that of TNF-α production. U937 cells treated with only PMA produced significantly more (P < 0.05) IL-1β than did control cultures (median only) at 4 to 24 h (22 to 44 pg/ml versus less than 15 pg/ml). The addition of E. coli or P. gingivalis LPS to PMA-treated U937 cells increased the IL-1β levels in the supernatant in a dose- and time-dependent manner (27 to 142 pg/ml). E. coli LPS (100 ng/ml) stimulated a peak response at 12 h, whereas the same dose of P. gingivalis LPS stimulated a weaker response which peaked by 8 h. E. coli LPS (100 ng/ml) induced significantly (P < 0.05) more IL-1β (120 pg/ml) than the same dose of P. gingivalis LPS by 24 h (92 pg/ml). Higher concentrations of IL-1 were present in supernatants of cultures stimulated with 1 μg P. gingivalis LPS per ml (150 pg/ml) than in cultures stimulated with a similar dose of E. coli LPS (110 pg/ml).

FIG. 1. Effects of P. gingivalis (Pg) and E. coli (Ec) LPSs on proliferative responses of U937 cells. U937 cells were incubated with medium or with the indicated concentrations of P. gingivalis or E. coli LPS for 72 or 96 h. Cultures were pulsed with [3H]TdR during the last 18 h of incubation. The graph indicates the PI; PI = (E − C)/C is the indexed level of [3H]TdR uptake by LPS-treated or control medium-treated U937 cells at the indicated time points. The amount of [3H]TdR taken up in control cultures ranged from 16,000 to 18,000 cpm. The data represent the mean PI ± the standard error of the mean of quadruplicate samples per experiment and three separate experiments.

FIG. 2. Kinetics of TNF-α production by PMA-treated U937 cells in response to E. coli (Ec) or P. gingivalis (Pg) LPS. U937 cells were cultured with control medium or 10 ng of PMA per ml for 48 h. Following incubation, control medium or LPS was added to a final concentration of 1.0 or 0.1 μg/ml and incubation was continued for various times. Culture supernatants were collected and cytokine release was analyzed by ELISA. The values are mean cytokine levels ± the standard error of the mean of triplicate samples and are representative of three separate experiments.

FIG. 3. Dose response of TNF-α production by PMA-treated U937 cells stimulated with E. coli (Ec) or P. gingivalis (Pg) LPS. U937 cells were cultured with 10 ng of PMA per ml for 48 h. Following incubation, medium, P. gingivalis LPS, or E. coli LPS was added at the indicated final concentrations and incubation was continued for 24 h. Culture supernatants were collected, and cytokine release was analyzed by ELISA. The values shown are mean cytokine levels ± the standard error of the mean of triplicate samples and are representative of three separate experiments.
The elutriated monocytes also responded to both LPS preparations (Fig. 4B). By 24 h, supernatants from cultures of elutriated monocytes incubated with *P. gingivalis* LPS contained significantly (*P < 0.05*) more IL-1 than did those from cultures incubated with *E. coli* LPS.

**IL-1ra production.** The kinetics and dose response of U937 cells to LPS were characterized by the absence of IL-1ra without PMA priming and high levels of IL-1ra in the supernatant of cells treated with PMA alone (19,380 to 29,000 pg/ml). *E. coli* LPS at 1 μg/ml was able to marginally increase IL-1ra levels in culture supernatants at 12 h. *P. gingivalis* LPS (0.1 μg/ml) induced supernatant levels of IL-1ra consistently above levels in cells treated with PMA alone by 4 to 12 h (30,600 to 33,800 pg/ml). These levels returned to the baseline by 24 h. The induction of IL-1ra release by PMA-treated U937 cells stimulated with LPS was not dose dependent. The various doses of *P. gingivalis* LPS tested did not increase IL-1ra levels in the supernatant above those produced by treatment with PMA only (data not shown).

Unstimulated, elutriated monocytes produced relatively high levels of IL-1ra (Fig. 4C). These cells were stimulated to release more IL-1ra after incubation with either LPS for 24 h. *E. coli* and *P. gingivalis* LPSs (100 ng/ml) induced significantly (*P < 0.05*) higher levels of IL-1ra than those seen in control cultures. At 5 μg/ml, *P. gingivalis* LPS induced the production of IL-1ra levels which were significantly (*P < 0.05*) above the background and above the level produced following treatment with a similar dose of *E. coli* LPS.

**Cytokine mRNA expression.** Cytopreparations of U937 cells and monocytes were evaluated by in situ hybridization for cytokine mRNA. Neither *P. gingivalis* nor *E. coli* LPS stimulated detectable levels of mRNA for the cytokines in non-PMA-treated U937 cells (Table 1). The PMA-treated U937 cell preparation contained cells with mRNAs for TNF-α, IL-1β, and IL-1ra. The proportion of PMA-treated cells expressing TNF-α and IL-1β mRNAs increased significantly (*P < 0.05*) after 4 h of incubation with LPS. PMA-treated cells stimulated with *P. gingivalis* LPS had more intense staining in a greater proportion of cells for both TNF-α and IL-1β mRNAs than did those stimulated with *E. coli* LPS (Fig. 5A). Neither LPS preparation influenced the level of IL-1ra mRNA expression by U937 cells over treatment with PMA alone.

LPS treatment did not visibly alter the morphology of the adherent elutriated monocytes as assessed by use of Wright’s stain (data not shown). Expression of mRNAs for TNF-α, IL-1β-, and IL-1ra by elutriated monocytes was significantly (*P < 0.05*) enhanced by the LPS preparations over treatment with medium alone (Table 1 and Fig. 5B). Following treatment with *P. gingivalis* LPS, more monocytic cells stained positively for TNF-α mRNA and IL-1β mRNA than after *E. coli* LPS treatment. The numbers of monocytes expressing IL-1ra mRNA were similar in cultures treated with *E. coli* LPS and those treated with *P. gingivalis* LPS.

**Surface CD14 expression.** To determine if the differential effects of the two LPS preparations might be associated with variations in LPS receptor expression in U937 cells and monocytes, flow cytometric analysis of surface CD14 levels was per-

![FIG. 4. Release of TNF-α, IL-1β, and IL-1ra by elutriated monocytes stimulated with *E. coli* (Ec) or *P. gingivalis* (Pg) LPS. Monocytes were cultured with medium or LPS for 24 h, and then culture supernatants were collected and cytokine levels were analyzed by ELISA. The values shown are mean cytokine levels ± the standard error of the mean of duplicate samples and are representative of four separate experiments. Means were significantly different from those of medium-treated (⁎) or *E. coli* LPS-treated (†) samples.](http://iai.asm.org/).
TABLE 1. Cytokine mRNA expression by U937 cells or elutriated monocytes after treatment with LPS and/or PMA

<table>
<thead>
<tr>
<th>Cell type and treatment</th>
<th>Cytokine mRNA expression (%) of positive cells</th>
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<tr>
<td></td>
<td>TNF-α</td>
</tr>
<tr>
<td>U937</td>
<td></td>
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<tr>
<td>Medium only</td>
<td>0</td>
</tr>
<tr>
<td>E. coli LPS (100 ng/ml)</td>
<td>0</td>
</tr>
<tr>
<td>P. gingivalis LPS (100 ng/ml)</td>
<td>0</td>
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<tr>
<td>PMA (10 ng/ml)</td>
<td>38 ± 6</td>
</tr>
<tr>
<td>PMA + E. coli LPS (100 ng/ml)</td>
<td>62 ± 5</td>
</tr>
<tr>
<td>PMA + P. gingivalis LPS (100</td>
<td>74 ± 5.5&lt;sup&gt;ad&lt;/sup&gt;</td>
</tr>
<tr>
<td>ng/ml</td>
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<tr>
<td>Control probe</td>
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<table>
<thead>
<tr>
<th>Elutriated monocytes</th>
<th></th>
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<tbody>
<tr>
<td>Medium only</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E. coli LPS (100 ng/ml)</td>
<td>38 ± 5'</td>
<td>52 ± 6'</td>
<td>72 ± 9'</td>
</tr>
<tr>
<td>P. gingivalis LPS (100 ng/ml)</td>
<td>57 ± 7&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>69 ± 7.5&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>67 ± 8'</td>
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<tr>
<td>Control probe</td>
<td>0</td>
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<sup>a</sup> Cells were incubated with medium or PMA for 48 h and then treated with medium or LPS and incubated for an additional 4 h (see Materials and Methods).

<sup>b</sup> Values are average frequencies ± the standard error of the mean (four to six slides per group) of positive cells in five microscope fields (magnification, ×10) per 100 cells counted.

<sup>c</sup> Significantly different (P < 0.05) from PMA-treated cells or medium-only controls.

<sup>d</sup> Significantly different (P < 0.05) from samples treated with PMA plus E. coli LPS or with E. coli LPS.

formed on these cell types. Eleven percent of the untreated U937 cells expressed surface CD14, with a mean fluorescence index (MFI) of 9.6. Addition of LPS alone did not significantly increase the number of positive cells or the fluorescence intensity. PMA-treated U937 cell preparations had higher percentages of CD14-positive cells (31% ± 4%) and greater mean fluorescence (MFI, 24 ± 4) than did untreated cells. In contrast to treatment with PMA and E. coli LPS, treatment of cultures with PMA and P. gingivalis LPS significantly (P < 0.05) increased both the percentage of positive cells (45% ± 7%) and the mean fluorescence (MFI, 35.5 ± 6).

The majority of the untreated, elutriated monocytes expressed CD14 on their surface, and the levels of expression were not affected by addition of either LPS (Fig. 6). The initial surface expression of CD14 as assessed by MFI was significantly (P < 0.05) increased after stimulation of cells with E. coli or P. gingivalis LPS (100 ng/ml). Higher doses of E. coli and P. gingivalis LPS further enhanced the mean fluorescence on monocytes as assessed by use of a fluorescence-activated cell sorter.

**DISCUSSION**

The mononuclear phagocyte plays a critical role in the regulation of the host response during chronic inflammation (40). The ability of microbial LPS to activate the mononuclear cell to produce inflammatory cytokines may directly affect the outcome of bacterium-induced inflammation by promoting either an acute tissue reaction, resolution, or chronic destruction (3). The present study investigated whether P. gingivalis LPS differs from E. coli LPS in the ability to induce TNF-α, IL-1β, and IL-1ra production by monocytes, which would support its role in promoting chronic inflammatory activation and tissue destruction as characterized in periodontitis. The expression of the LPS receptor CD14 on the monocytes was also evaluated to determine its possible role in the activation process.

The LPS of the periodontopathogen P. gingivalis demonstrates chemical and biological differences from classical E. coli LPS (12, 25, 28). P. gingivalis, in comparison to E. coli LPS, exhibits less endotoxic activity in vivo (25, 28). It has also been shown that P. gingivalis LPS may be similar to E. coli LPS in terms of mitogenicity, polyclonal B-cell activation, stimulation of IL-1 production (20), and the ability to induce TNF-α (33). However, other investigators have shown that P. gingivalis LPS, in contrast to E. coli LPS, does not induce epithelial cells to express E-selectin or promote neutrophil adhesion, which may facilitate bacterial colonization of the gingival tissue and persistence (7). Our results show that P. gingivalis LPS, compared to E. coli LPS, induced similar or higher levels of cytokine production by monocytes and that the higher cytokine expression related to upregulation of CD14 expression.

Both U937 cells and human peripheral blood monocytes were used to evaluate cellular responses to the two LPS preparations. When the abilities of the LPS preparations to stimulate U937 cells were assessed, it was noted that at the higher concentrations of LPS tested, P. gingivalis LPS promoted cellular proliferation while a similar amount of E. coli LPS was inhibitory. This finding may be explained by a lesser toxicity of P. gingivalis LPS than E. coli LPS or by different mechanisms of cell activation. In gingival tissue, the initial proliferation of

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**FIG. 5.** Expression of cytokine mRNA by LPS-treated U937 cells and elutriated monocytes. PMA-treated U937 cells (A) or untreated monocytes (B) were incubated with 100 ng of E. coli (Ec) or P. gingivalis (Pg) LPS per ml for 24 h, harvested by gentle scraping, and spun onto glass slides. Cells were fixed, and cytokine mRNA was detected by in situ hybridization. The fields shown are from representative slides of six (U937 cells) or four (monocytes) separate experiments performed in duplicate.
The ability of *P. gingivalis* LPS to stimulate TNF-α release is shown. The U937 cells used in this study required PMA stimulation to become sensitive to LPS stimulation for a cytokine response, whereas the elutriated monocytes used were sensitized without pretreatment. This is likely due to the more advanced state of differentiation of the monocytes compared to the untreated cell line, particularly with regard to expression of LPS receptors (30). Phorbol ester treatment of U937 cells induces them to differentiate into more macrophase-like cells (e.g., more extensive cytoplasm, increased protein synthesis, decreased mitosis, and increased HLA-DR and Fc-γ receptor expression) (19, 26, 31, 35). *P. gingivalis* LPS-stimulated release of TNF-α from both cell types was dose dependent at concentrations of 10 ng/ml to 1 μg/ml. *E. coli* LPS stimulated maximum TNF-α release at a concentration of 10 ng/ml and did not promote greater TNF-α release at higher concentrations. These results extend the findings of others (33) showing the induction of similar levels of TNF-α by human peripheral blood monocytes stimulated with either *E. coli* or *P. gingivalis* LPS at ≤10 ng/ml. The ability of *P. gingivalis* LPS to stimulate TNF-α release at higher doses may allow the establishment of a chronic inflammatory process as the anaerobic *P. gingivalis* bacteria multiply in the diseased periodontal pocket. TNF-α released by the mononuclear phagocyte can target other inflammatory and accessory cells, as well as function as an autocrine activator. This response may lead to periodontal destruction via processes including neutrophil chemotaxis and degranulation, fibroblast production of collagenase, and osteoclast activation for bone resorption.

Unlike the TNF-α response, the IL-1β response to each LPS preparation was the same at all of the concentrations tested. This may reflect differences in the regulation of TNF and IL-1 responses to LPS, a finding that has been previously documented (5, 6). The induction of these two cytokines appears to involve separate second-messenger systems which relay the LPS signal to the monocyte nucleus. The differences in TNF and IL-1 release which we observed in the LPS dose-response experiments might be explained by the separate routes of intracellular signaling which are used to activate mRNA transcription of the two cytokines. IL-1β may play a dual role in periodontal disease processes, as both a potent inducer of osteoclasts and an activator of B cells. It can therefore elicit both destruction of alveolar bone and protection from pathogenic flora colonization (10, 11, 16).

In our studies, we observed high levels of IL-1ra which were 100 to 200 times those of IL-1β. This amount of antagonist is required to effectively block the binding of IL-1 to its cellular receptor (14). The inhibition of IL-1 activity can decrease inflammatory destructive processes and can dampen IL-1-associated immune activation (16). IL-1ra production by the mononuclear phagocyte can function to protect tissues from an acute inflammatory response and may be involved in the healing phase of inflammation subsequent to periods of active destruction (1, 13). However, it is not possible to discern from this study how LPS could influence a balance between IL-1 and IL-1ra production.

In situ hybridization experiments were performed to correlate cytokine mRNA induction with the observed protein expression following LPS stimulation of monocytic cells. Studies examining LPS cytokine induction in mononuclear phagocytes usually measure average quantities of cytokine mRNA induced in the entire population of cells. In this study, we utilized sensitive in situ hybridization methods to analyze the production of cytokine mRNAs by individual cells in the U937 and monocyte populations. Addition of PMA to the U937 cells caused expression of detectable levels of TNF-α mRNA, which were increased by *E. coli* LPS and further augmented by *P. gingivalis* LPS. Regulation of TNF-α protein release was associated with mRNA induction as observed by in situ hybridization. *P. gingivalis* LPS induced both TNF transcription and protein release. These findings are compatible with the potential role of *P. gingivalis* LPS in maintaining TNF-α expression in periodontal tissues and thereby promoting inflammation, release of prostaglandins and matrix metalloproteinases, osteoclast activation, and eventual bone loss.

Flow cytometric analyses demonstrated induction of CD14 expression in U937 cells (increased percentage of positive cells and increased MFI) and monocytes (increased MFI) caused by the addition of LPS, with *P. gingivalis* LPS eliciting a greater number of CD14-positive cells and higher MFIs than *E. coli* LPS. Increased expression of LPS receptors on the mononuclear phagocytes may account for their enhanced ability to produce TNF-α when treated with increasing doses of *P. gingivalis* LPS. This idea is supported by the finding that pretreatment of human monocytes with antibody to CD14 (MY4) resulted in a reduction of TNF-α mRNA and protein levels after LPS stimulation (33). As more LPS receptors are avail-

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**FIG. 6. Induction of LPS receptor (CD14) expression by LPS-treated, elutriated monocytes.** Monocytes were incubated with the indicated amounts of *E. coli* (Ec) or *P. gingivalis* (Pg) LPS for 24 h, harvested, and examined for surface expression of CD14 by flow cytometry. The histograms are representative of four separate experiments, and percentages of CD14-positive cells and MFIs reflecting the relative number of CD14 molecules per cell are shown. **Vol. 65, 1997**
able on the cell surface, the cytokine response to the LPS may be further enhanced. In a periodontal lesion, the cells could respond to increasing levels of LPS and promote chronic activation.

Our studies have shown that there are differences in the manner of activation of mononuclear phagocytes by LPS from the periodontal pathogen *P. gingivalis* compared to *E. coli* LPS. This included differences in promotion of proliferation, cytokine mRNA and protein production, and expression of the LPS receptor CD14. The ability of *P. gingivalis* LPS to promote the expression of cytokines such as TNF-α, IL-1, IL-1ra, IL-1β, and IL-6 receptor CD14. The ability of *P. gingivalis* LPS to promote the expression of cytokines such as TNF-α, IL-1, IL-1ra, IL-1β, and IL-6 receptor CD14. The ability of *P. gingivalis* LPS to promote the expression of cytokines such as TNF-α, IL-1, IL-1ra, IL-1β, and IL-6 receptor CD14.

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