Inhibitory effects of formoterol on lipopolysaccharide-induced premature delivery through modulation of proinflammatory cytokine production in mice

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Previous studies have demonstrated that formoterol, a β₂-adrenoceptor agonist, has potent tocolytic effects in rats. The aim of the present study was to determine whether formoterol treatment affects proinflammatory cytokine production in a lipopolysaccharide (LPS)-treated premature delivery mouse model. Formoterol was continuously administered by osmotic pump and the number of fetuses in the uteri were counted. Samples of amniotic fluid and plasma were collected 8 and 16 h after systemic administration of LPS. LPS induced premature delivery and an increase in prostaglandin F₂α (PGF₂α), interleukin 1α (IL-1α), IL-6 and IL-10 in the amniotic fluid, and an increase in IL-6 in plasma. Formoterol blocked all changes except the increase in IL-10. These data indicate that formoterol exerts inhibitory effects on proinflammatory cytokine production, and these effects may play an important role in the prevention of premature delivery.

Introduction

Formoterol fumarate (formoterol) is a highly potent long-lasting β₂-adrenoceptor agonist used for asthma therapy. Other drugs, such as ritodrine, are used extensively for the prevention of premature delivery in the clinical field. Widespread use of β-adrenoceptor agonists is not associated with any significant improvement in neonatal outcome (Johnson, 1993). However, Shinkai and Takayama (2000) demonstrated that formoterol suppresses rat uterine activity at 100–1000-fold lower doses than ritodrine. Premature delivery is associated with increased concentration of proinflammatory cytokines in the amniotic fluid (Gomez et al., 1997). Romero et al. (1992, 1993) proposed that the proinflammatory cytokines interleukin 1(IL-1) and IL-6 are predictors of microbial colonization of the amniotic cavity and premature delivery in the setting of infection. An increase in IL-1 and IL-6 stimulates prostaglandin production, causing uterine contraction (Mitchell et al., 1990, 1991). IL-6 and IL-8 are known to increase during human cervical ripening, and presumably play an important role in uterine contraction (Sennstrom et al., 2000). IL-6 causes an increase in the activity of the gelatinases or type IV collagenases matrix metalloproteinase 2 (MMP-2) and MMP-9 in human cytotrophoblastic cells (Meisser et al., 1999).

IL-10 generally inhibits the transcription of proinflammatory cytokines such as IL-1, tumour necrosis factor α (TNF-α), IL-6 and IL-8 (Moore et al., 1993; Wang et al., 1995). IL-10 is produced in monocytes and macrophages as well as in gestational tissues, including amnion, chorion and decidual cells (Trautman et al., 1997). IL-10 concentrations in amniotic fluid of women who experience preterm labour are lower than those seen in that of women who undergo normal term delivery in the absence of infection. However, an increase in IL-10 has been reported for preterm labour associated with intrauterine infection, indicating an immunoregulatory role for IL-10 (Greig et al., 1995).

Studies have also indicated that β-adrenergic agonists are involved in immunoregulatory processes. For example, adrenaline induces IL-6 in endothelial cells and enhances lipopolysaccharide (LPS)-induced IL-6 production (Gornikiewicz et al., 2000). In contrast, the β₂-adrenoceptor agonist, clenbuterol, suppresses the LPS-induced release of IL-6 and TNF-α from macrophages (Izeboud et al., 1999), and isoproterenol and formoterol decrease IL-6 and TNF-α gene transcription in rat renal macrophage cells (Nakamura et al., 1999). Furthermore, IL-10 secretion induced by LPS is enhanced by the β₂-adrenoceptor agonist TA2005 in macrophages (Izeboud et al., 2000), whereas terbutaline does not affect LPS-induced IL-10 production in rat mesangial cells (Nakamura et al., 2000). Thus, the effects of β-adrenoceptor agonists on cytokine production may depend on the experimental conditions, such as the cell

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strains used or the β2-adrenoceptor ligand. In particular, it remains unclear whether β2-adrenoceptor agonists influence cytokine secretion by amnion tissues. If β2-adrenoceptor agonists such as formoterol cause not only relaxation of the uterus but also the secretion of cytokines, they could be used for women at high risk of premature delivery. Therefore, the present study investigated the effects of formoterol on LPS-induced IL-6, IL-1α, IL-10 and prostaglandin F2α (PGF2α) production in vivo.

Materials and Methods

Animals

C3H/HeN strain pregnant mice (Charles River, Yokohama) at day 15 of gestation were used. They were housed at 23 ± 2°C, relative humidity of 55 ± 15% and with a 12 h light:12 h dark cycle (light on at 8:00 h), and allowed access to mouse or rat diet (F-2, pelleted form; Funabashi Farm, Funabashi) and tap water ad libitum throughout the experiment. All experimental procedures were carried out in accordance with the in-house guidelines of the Institutional Animal Care and Use Committee of Saitama Daiichi Pharmaceutical Co Ltd.

Drugs

Formoterol fumarate was obtained from Yamanouchi Pharmaceutical Co. Ltd (Tokyo). LPS was purchased from Sigma Chemical Co. (St Louis, MO). Both drugs were dissolved in 0.9% (w/v) physiological saline (Otsuka Pharmaceutical Co. Ltd, Tokyo).

Procedure

Osmotic pumps (Model 2001D, Alza Corporation, Mountain View, CA) were filled with 200 μl formoterol (Yamanouchi) or saline and implanted subcutaneously into the backs of mice on day 15 of gestation, under ether anaesthesia. The osmotic pumps injected drug solution with a pumping rate of 7.9 μl h⁻¹ for 24 h. A dose of LPS (30 μg ml⁻¹) that gave consistent premature delivery without maternal death was administered intraperitoneally 4 h after implantation and mice were killed 8 or 16 h thereafter. Saline solution was used as a control and comparisons were made of the numbers of total fetuses and live fetuses in uteri. Samples of amniotic fluid and plasma were collected by injection syringe (1 ml) and pooled from each individual mouse, and stored at −80°C until assayed for PGF2α (Cayman Chemical, Ann Arbor, MI) and IL-1α, IL-6 and IL-10 (Amersham Pharmacia Biotech, Little Chalfont) using ELISA kits.

Statistical analysis

The results, expressed as mean ± SEM, were analysed by Kruskal–Wallis non-parametric one-way ANOVA. Further statistical analysis for post hoc comparisons was accomplished with a Steel’s non-parametric multiple comparison test. Student’s t test was used for pairs of sample means. The criterion for significance was P < 0.05 in all statistical evaluations.

Results

The number of fetuses in uteri before LPS treatment (30 μg ml⁻¹) did not vary among the groups (Tables 1 and 2). Treatment of pregnant mice with LPS caused a decrease in the number of total fetuses and live fetuses in uteri 16 h after administration, and this was used as an index of premature delivery (Table 2). This decrease was significantly inhibited by the injection of formoterol (0.006 or 0.06 mg kg⁻¹ h⁻¹).

LPS treatment increased the IL-6 concentration in plasma 16 h after administration, but did not change PGF2α or IL-10 concentration (Table 3). The concentration of IL-1α in plasma was lower than the limit of detection in all samples. Formoterol treatment significantly reduced the increase in IL-6 induced by LPS.

LPS significantly increased PGF2α and IL-6 concentrations in the amniotic fluid 8 h after administration and to a greater extent 16 h after administration (Figs 1 and 2).

Table 1. The influence of formoterol administration on the number of fetuses in uteri 8 h after lipopolysaccharide (LPS) treatment in mice

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Number of fetuses in uteri</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7.0 ± 0.5</td>
</tr>
<tr>
<td>LPS (30 μg per mouse)</td>
<td>8.8 ± 0.8</td>
</tr>
<tr>
<td>+ formoterol (0.006 mg kg⁻¹ h⁻¹)</td>
<td>7.4 ± 0.2</td>
</tr>
<tr>
<td>+ formoterol (0.06 mg kg⁻¹ h⁻¹)</td>
<td>6.8 ± 0.8</td>
</tr>
</tbody>
</table>

LPS was administered intraperitoneally 4 h after implanting osmotic pumps containing formoterol solution. Values represent the mean ± SEM (n = 5 or 6 mice). The numbers of live fetuses in uteri are shown in parentheses.
Table 2. The influence of formoterol administration on the number of fetuses in uteri 16 h after lipopolysaccharide (LPS) treatment in mice

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Number of fetuses in uteri</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>8.3 ± 0.5 (8.3)</td>
</tr>
<tr>
<td>LPS (30 µg per mouse)</td>
<td>7.2 ± 0.4 (2.2 ± 1.0)</td>
</tr>
<tr>
<td>+ formoterol (0.006 mg kg⁻¹ h⁻¹)</td>
<td>6.3 ± 1.0 (5.3 ± 3.4)</td>
</tr>
<tr>
<td>+ formoterol (0.06 mg kg⁻¹ h⁻¹)</td>
<td>7.3 ± 0.5 (6.3 ± 1.0)</td>
</tr>
</tbody>
</table>

LPS was administered intraperitoneally 4 h after implanting osmotic pumps containing formoterol solution. Values represent the mean ± SEM (n = 5 or 6 mice). The numbers of live fetuses in uteri are shown in parentheses. *P < 0.01 versus control; **P < 0.05; ***P < 0.01 versus LPS alone.

Table 3. Changes in cytokine and prostaglandin F₂α (PGF₂α) plasma concentration in mice 16 h after administration of lipopolysaccharide (LPS) alone or with formoterol

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Concentration (pg ml⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>PGF₂α: 1688.5 ± 190</td>
</tr>
<tr>
<td></td>
<td>IL-1α: ND</td>
</tr>
<tr>
<td></td>
<td>IL-6: 33.4 ± 13</td>
</tr>
<tr>
<td></td>
<td>IL-10: 3598.9 ± 323</td>
</tr>
<tr>
<td>LPS (30 µg per mouse)</td>
<td>PGF₂α: 1425.0 ± 216</td>
</tr>
<tr>
<td></td>
<td>IL-1α: ND</td>
</tr>
<tr>
<td></td>
<td>IL-6: 331.4 ± 57*</td>
</tr>
<tr>
<td></td>
<td>IL-10: 3922.2 ± 333</td>
</tr>
<tr>
<td>− formoterol (0.006 mg kg⁻¹ h⁻¹)</td>
<td>PGF₂α: 1308.0 ± 213</td>
</tr>
<tr>
<td></td>
<td>IL-1α: ND</td>
</tr>
<tr>
<td></td>
<td>IL-6: 132.4 ± 10⁺</td>
</tr>
<tr>
<td></td>
<td>IL-10: 4357.0 ± 324</td>
</tr>
<tr>
<td>+ formoterol (0.06 mg kg⁻¹ h⁻¹)</td>
<td>PGF₂α: 1203.0 ± 165</td>
</tr>
<tr>
<td></td>
<td>IL-1α: ND</td>
</tr>
<tr>
<td></td>
<td>IL-6: 108.1 ± 11⁺</td>
</tr>
<tr>
<td></td>
<td>IL-10: 4304.5 ± 283</td>
</tr>
</tbody>
</table>

Values represent the mean ± SEM (n = 9 or 10 mice). Interleukin 1α (IL-1α) concentrations were lower than the limit of detection (ND). *P < 0.01 versus control; **P < 0.05; ***P < 0.01 versus LPS alone.

Fig. 1. Effects of formoterol on lipopolysaccharide (LPS)-induced increase of prostaglandin F₂α (PGF₂α) in amniotic fluid in mice (□) 8 h and (■) 16 h after administration of LPS. Values are mean ± SEM (n = 8–11 mice). *P < 0.05; **P < 0.01 versus control; *P < 0.01 versus LPS alone.

Fig. 2. Effects of formoterol on lipopolysaccharide (LPS)-induced increase of interleukin 6 (IL-6) in amniotic fluid in mice (□) 8 h and (■) 16 h after administration of LPS. Values are mean ± SEM (n = 8–11 mice). *P < 0.05; **P < 0.01 versus control; *P < 0.05; ***P < 0.01 versus LPS alone.

Discussion

IL-1α and IL-10 concentrations were also increased after 16 h (Figs 3 and 4).

Combined treatment of LPS with formoterol resulted in a significant suppression of the change in PGF₂α, IL-6 and IL-1α at 0.006 or 0.06 mg formoterol kg⁻¹ h⁻¹. The concentration of IL-10 was not affected by the formoterol treatment.

Formoterol administration inhibited premature delivery induced by LPS in mice and increased the number of live fetuses in uteri 16 h after treatment with LPS. However, formoterol administered intraperitoneally twice a day did not influence LPS-induced premature delivery (data not shown). Osmotic pumps can maintain the blood concentration of formoterol for over 20 h. Thus, it may
In the present study, the β2-adrenoceptor agonist formoterol ameliorated the LPS-induced decrease in the percentage of fetuses in uteri (an index of premature delivery) and this appears to be related to the suppression of the increase in concentrations of IL-1α, IL-6 and PGF2α in the amniotic fluid. Moreover, formoterol inhibits an increase in IL-6 in plasma. There is much evidence that β2-adrenoceptor agonists may be involved in immunoregulation, although little is known about the signal pathways involved. However, Nakamura et al. (2001) demonstrated that downregulation of Shiga toxin 2-induced TNF-α production by terbutaline is mediated by an inhibitory effect of β2-adrenoceptor activation on the nuclear factor κB (NF-κB), exerted through a cAMP–protein kinase pathway and a cAMP-independent mechanism. Moreover, an increase in intracellular CAMP concentration may decrease NF-κB-mediated TNF-α gene transcription (Oliver et al., 1996). The present study did not examine whether formoterol influences the production of TNF-α. Future investigations will concentrate on early TNF-α production in order to clarify the inhibitory mechanisms of formoterol. However, the present study has shown that formoterol inhibits IL-1α and IL-6 production in amnion tissues after the synthesis of PGF2α. This effect may also be associated with the suppression of activation or transcription of NF-κB or TNF-α.

Formoterol administration did not affect the LPS-induced increment in the anti-inflammatory cytokine inhibitor IL-10 in amniotic fluid in the present study. IL-10 may cause inhibition of NF-κB activation in LPS-stimulated human monocytes (Wang et al., 1995), and thus suppress cytokine production. It remains unclear whether an increase in the IL-10 concentration in amniotic fluid may contribute to negative feedback in the cytokine network, but it should be noted that the plasma concentration of IL-10 is approximately 160-fold higher than that in amniotic fluid in normal pregnant mice. Thus, the effect of IL-10 on IL-1α or IL-6 might be expected to be much less in amniotic fluid than in plasma. In the present study, LPS treatment increased the IL-10 concentration in amniotic fluid, albeit only approximately threefold compared with the control. The fact that IL-10 was not affected by formoterol, despite the significant reduction in other cytokines, indicates a beneficial effect with regard to the suppression of premature delivery.
In conclusion, the present study has shown that formoterol can protect against premature delivery induced by systemic administration of LPS in pregnant mice, and the associated reduction in the cytokines IL-1α and IL-6. Whether this activity is mediated through β2-adrenoceptors remains to be clarified, but the results of this study indicate that formoterol may have potential for the treatment of women at high risk of premature delivery.

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References


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