The effect of prostaglandin E₂, iloprost and cAMP on both nitric oxide and tumour necrosis factor-α release in J774 macrophages has been studied. Both prostaglandin E₂ and iloprost inhibited, in a concentration-dependent fashion, the lipopolysaccharide-induced generation of nitric oxide and tumour necrosis factor-α. The inhibitory effect of these prostanoids seems to be mediated by an increase of the second messenger cAMP since it was mimicked by dibutyryl cAMP and potentiated by the selective type IV phosphodiesterase inhibitor RO-20-1724. Our results suggest that the inhibition of nitric oxide release by prostaglandin E₂ and iloprost in lipopolysaccharide-activated J774 macrophages may be secondary to the inhibition of tumour necrosis factor-α generation, which in turn is likely to be mediated by cAMP.

Key words: cAMP, Macrophages, Nitric oxide, Phosphodiesterase inhibitor, Prostaglandins, Tumour necrosis factor

Introduction

Macrophages activated with bacterial lipopolysaccharide release a variety of mediators including nitric oxide (NO), tumour necrosis factor (TNF-α) and prostaglandins, namely prostaglandin E₂ (PGE₂) and prostacyclin (PGI₂). The cytotoxic properties of activated macrophages depend, at least in part, on the biological activities of these mediators. Thus the synthesis of NO from the amino acid L-arginine has been shown to be a major cytotoxic mechanism of activated macrophages. Moreover NO has been identified as an effector molecule of the cytotoxic effects produced by TNF-α in bovine endothelial cells. Conversely, PGE₂ and PGI₂ inhibit the cytotoxic properties of activated macrophages. Furthermore, increasing evidence suggests that the interaction existing within the biological actions of NO, prostaglandins and TNF-α may result in a mutual regulation of their synthesis and/or release. In fact TNF-α has been reported to induce NO synthase in murine peritoneal macrophages and bovine endothelial cells. TNF-α increases PGE₂ production in human synovial cells and human dermal fibroblasts, as well as PGI₂ generation in human endothelial cells. Conversely, PGE₂ has been shown to down-regulate the generation of TNF-α in macrophages of different origin and HL-60 cells. Moreover it has been reported that the release of TNF-α by macrophages is inhibited by cAMP, a second messenger for both PGE₂ and PGI₂.

We have shown that PGE₂ and the stable analogue of PGI₂, iloprost, inhibited the induction of NO synthase in lipopolysaccharide-activated J774 murine macrophages. We hypothesized that the inhibition of NO synthase induction could be secondary to an increase in cAMP levels in the activated macrophages. This hypothesis was also supported by the inability of both prostaglandin F₂₀ (PGF₂₀) and the stable analogue of thromboxane A₂ (TXA₂), U46619, which do not enhance cAMP levels, to modify NO generation. However, since TNF-α induces NO synthase in murine macrophages and PGE₂ has been shown to inhibit TNF-α release from these cells, the inhibition of NO synthase induction by PGE₂ could also be secondary to the down-regulation of TNF-α in J774 cells.

In the light of the above considerations we have studied the effect of PGE₂, PGI₂ and cAMP on the production of NO and TNF-α by lipopolysaccharide-stimulated J774 macrophages.

Materials and Methods

The murine monocyte macrophage cell line J774 (American Tissue Culture Catalogue TIB 67, page 231) was grown in Dulbecco’s modified Eagle’s medium (Gibco) at 37°C as described previously. The cells were plated in 24-well culture plates (Falcon) at a density of 2.5 × 10⁵ cells/ml and allowed to adhere at 37°C in 5% CO₂/95% air for 2 h. Thereafter the medium was replaced with fresh medium, cells were activated with lipopolysaccharide (0.1 µg/ml) from Salmon-
Macrophage activation by prostaglandins

*nella typhosa* (Difco) and incubated in the presence of various concentrations (see Results) of test compounds: PGE₂, PGF₂α and dibutyryl cAMP (Sigma), iloprost (Schering), RO-201724 (Biomol).

NO was measured as nitrates (NO₃⁻, nmol per 10⁶ cells) accumulated in the incubation media 24h after lipopolysaccharide challenge. A spectrophotometric assay based on the Griess reaction was used.

The level of TNF-α (U/ml) in the cell medium, 3h after lipopolysaccharide challenge, was assessed in WEHI-164 cells by a biological assay using recombinant human TNF-α (Sigma) as reference standard and rabbit antimurine TNF-α (Genzyme) antiserum which cross-reacts with rat TNF-α in order to assess the specificity of TNF-α-dependent cytolytic activity.

Data are expressed as percent of control release (mean ± standard error of the mean of n observations). Comparisons were made by the unpaired two-tailed Student's t-test. The level of statistically significant difference was defined as p < 0.05.

Results

The production of NO₂⁻ by unstimulated J774 macrophages was undetectable (< 1 nmol per 10⁶ cells in 24h, n = 6). The cells stimulated with lipopolysaccharide (0.1 μg/ml) released, as previously reported (Marotta et al.¹³), substantial amounts of NO, measured as NO₂⁻ (64.5 ± 2.3 nmol per 10⁶ cells in 24h, n = 8). When the cells were stimulated in the presence of dibutyryl cAMP (10⁻⁴ - 10⁻⁶ M), PGE₂ (10⁻⁶ - 10⁻⁸ M) or iloprost (10⁻⁷ - 10⁻⁹ M), added concomitantly with LPS, a concentration-dependent decrease of NO₂⁻ accumulation was observed (Fig. 1). PGE₂, iloprost and cAMP, at any of the concentrations tested, did not affect NO₂⁻ generation when added to the cells 6h after lipopolysaccharide challenge (data not shown). Conversely, PGF₂α (10⁻⁶ - 10⁻⁸ M) did not significantly affect NO₂⁻ accumulation when added concomitantly with lipopolysaccharide or 6h later (data not shown). The inhibition produced by 10⁻⁴ M dibutyryl cAMP was about 50% (p < 0.01) and was virtually superimposable on the inhibition produced by 10⁻⁸ M PGE₂ and 10⁻⁷ M iloprost. The selective inhibitor of cAMP-specific phosphodiesterase type IV, RO-201724,¹⁵ significantly (p < 0.01) increased the inhibition induced by dibutyryl cAMP. In fact, in the presence of 10⁻⁴ M RO-201724, the inhibition of NO₂⁻ accumulation by 10⁻⁴ M dibutyryl cAMP was significantly increased from about 50% to about 70% (Fig. 1). RO-201724 also potentiated the inhibitory action of PGE₂ and iloprost on NO₂⁻ generation (Fig. 1).

We have also studied the effect of PGE₂, PGF₂α (iloprost) and cAMP (dibutyryl cAMP) on TNF-α release from lipopolysaccharide-activated J774 cells. Three h after lipopolysaccharide-challenge these cells released 297 ± 20.5 U/ml of TNF-α (n = 8), compared to the undetectable release by unstimulated cells (< 1 U/ml in 3h, n = 8). Both PGE₂ (10⁻⁶ - 10⁻⁸ M) and iloprost (10⁻⁷ - 10⁻¹² M) produced a concentration-dependent inhibition of TNF-α release (Fig. 2). PGF₂α (10⁻⁶ - 10⁻⁸ M) did not produce any effect (data not shown). It is interesting to note that iloprost, as observed for NO₂⁻ generation, was more potent than PGE₂, also an inhibitor of TNF-α release. Moreover, both prostanooids significantly inhibited (p < 0.01) TNF-α release at concentrations which were virtually ineffective on NO₂⁻ production (10⁻⁸ M PGE₂ or 10⁻⁹ M iloprost). The phosphodiesterase inhibitor RO-201724 (10⁻⁸ M) potentiated the effect of iloprost for significant inhibition (p < 0.01) of TNF-α release was observed at concentrations of 10⁻¹¹ and 10⁻¹² M, (10.5 ± 1.1% and 41.1 ± 3.7% of control release, respectively; n = 4). Dibutyryl cAMP (10⁻⁴ - 10⁻⁶ M) inhibited lipopolysaccharide-induced TNF-α release in a concentration-dependent fashion (Fig. 2). Moreover, as observed for PGE₂ and iloprost, dibutyryl cAMP was more potent as an inhibitor of TNF-α release.
FIG. 2. Effect of prostaglandin E₂ (PGE₂, open bars) iloprost (hatched bars) and dibutyryl cAMP (dBcAMP, cross-hatched bars) on TNF-α release by J774 murine macrophages 3 h after lipopolysaccharide challenge (0.1 μg/ml). Data are expressed as mean ± standard error of the mean of five to six experiments. *p < 0.05, **p < 0.01 vs. control (lipopolysaccharide alone = 100% release).

Discussion

We have shown that PGE₂ and PGF₂α, and its stable analogue iloprost, which are known to activate adenylate cyclase, inhibit the induction of NO synthase in lipopolysaccharide-activated J774 macrophages. We also demonstrated that this action was not shared by PGF₂α and the stable analogue of TXA₂, U46619, which do not enhance cAMP levels. The results of the present study show that cAMP, as its permeable form dibutyryl cAMP, inhibits lipopolysaccharide-induced NO release by J774 macrophages, and confirm that this release is inhibited by PGE₂ and iloprost but not by PGF₂α. The selective type IV phosphodiesterase inhibitor, RO-201724, potentiated not only the inhibitory effect of cAMP but also the effect of the two prostanooids. In the light of these findings our results strongly suggest that the inhibitory action of the two prostanooids on NO synthase induction in lipopolysaccharide-activated J774 macrophages is mediated by cAMP. This evidence is also supported by recent results showing that in murine peritoneal macrophages, cAMP is an intermediate in the down-regulation of NO synthase by prostaglandins.

Our results also show that PGE₂ and iloprost, but not PGF₂α, inhibit in a concentration-dependent fashion of lipopolysaccharide-induced TNF-α production by J774 macrophages. This effect was exhibited also by cAMP. The phosphodiesterase inhibitor RO-201724 potentiated this action. PGF₂α was unable to inhibit lipopolysaccharide-induced TNF-α release by J774 macrophages. These data suggest that, as observed for NO generation, the inhibitory action of the two prostanooids on TNF-α release is likely to be mediated by cAMP. In this respect it is interesting to note that all the tested compounds were more potent in inhibiting TNF-α than NO₂ production. Since NO seems to be the effector molecule of the cytotoxic activity of TNF-α, and PGE₂ and iloprost modulate the production of TNF-α and NO, it could be hypothesized that the inhibitory action of the two prostanooids on NO synthase induction might be secondary to the inhibition of TNF-α generation which seems to be mediated by cAMP. This hypothesis appears conceivable considering that in macrophages lipopolysaccharide stimulates not only TNF-α and NO but also a sustained production of the prostaglandins, following the expression of inducible cyclooxygenase. In this light the down-regulation of TNF-α and consequently of NO production by endogenous prostaglandins may represent a relevant feed-back mechanism in modulating the cytotoxic effects of a sustained NO production following immunological stimulation.

References

1. Hibbs Jr JB, Taintor RR, Yavitt J, Rachlin EM. Nitric oxide: a cytotoxic activated macrophages effecter molecule. *Biochem Biophys Res Commun* 1988; 157:87–94.
2. Kuziel S, Spengler M, May MA, Spengler M, Larick J, Remick D. Prostaglandin E₂ regulates macrophages-derived tumor necrosis factor gene expression. *J Biol Chem* 1998; 263: 5310–5314.
3. Bonita E, Ben-Efrim M, Lenzier and prostaglandins mutually govern the antitumor potential of macrophages. In: Garaci E, Paolenti R, Santoro MG, eds. *Prostaglandins and Cancer Research*. Heidelberg, Springer Verlag, 1987; 193–201.
4. Estrada C, Gomez C, Martin S, Menezes S, Gonzalez C. Nitric oxide mediates tumor necrosis factor-α cytotoxicity in endothelial cells. *Biochem Biophys Res Commun* 1992; 186: 475–482.
5. Draper JC, Wettenbild H, Hibbs Jr JB. Interferon-γ and tumor necrosis factor induce the l-arginine-dependent cytotoxic effector mechanism in murine macrophages. *Eur J Immunol* 1998; 18: 1587–1592.
6. Dayer J, Beutler B, Cerami A. Cachectin/tumour necrosis factor stimulates collagenase and prostaglandin E₂ production by human synovial cells and dernal fibroblasts. *J Exp Med* 1985; 162: 2163–2167.
7. Backwich P, Chensue S, Larrock J, Kunkel S. Tumor necrosis factor stimulates interleukin-1 and prostaglandin E₂ production in resting macrophages. *Biochem Biophys Res Commun* 1986; 136: 94–101.
8. Peters T, Karkel K, Decker K. Interdependence of tumor necrosis factor, prostaglandin E₂, and protein synthesis in lipopolysaccharide-exposed rat Kupffer cells. *Eur J Biochem* 1990; 191: 383–389.
9. Kawakami M, Ishibashi S, Ogawa H, Murase T, Takaku F, Shibata S. Cachectin/TNF as well as interleukin-1 induces prostacyclin synthesis in cultured vascular endothelial cells. *Biochem Biophys Res Commun* 1986; 141: 462–467.
Macrophage activation by prostaglandins

dependently regulated by prostaglandins. J Immunol 1988; 141: 2388–2393.

11. Mohri M, Sriggs DR, Kufe D. Effects of lipopolysaccharide on phospholipase A2 activity and tumor necrosis factor expression in HL-60 cells. J Immunol 1990; 144: 2081–2087.

12. Endres S, Pulle HJ, Sinha D, Stoll D, Dinarello CA, Gerzer R, Weber PC. Cyclic nucleotides differentially regulate the synthesis of tumour necrosis factor-α and interleukin-1β by human mononuclear cells. Immunology 1991; 72: 56–60.

13. Marotta P, Sautebin L, Di Rota M. Modulation of the induction of nitric oxide synthase by eicosanoids in the murine macrophages cell line J774. Br J Pharmacol 1992; 107: 640–641.

14. Green LC, Wagner DA, Glgowsky JS, Skipper PL, Wishnok JS, Tannenbaum SR. Analysis of nitrate, nitrite and [15-N] nitrite in biological fluid. Analyt Biochem 1982; 126: 131–136.

15. Garrels IM, Zijlstra Pj, Tak CJAM, Borst II, Beckman I, Ben Efraim S. A comparison between two methods for measuring necrosis factor in biological fluids. Agents Actions 1993; 38: C90–91.

16. Reeves ML, Leigh BK, England PJ. The identification of a new cyclic nucleotide phosphodiesterase activity in human and guinea-pig cardiac ventricle. Biochim Biophys Acta 1987; 241: 535–541.

17. Raddassi K, Petit SF, Lemaire G. LPS-induced activation of primed murine macrophages is modulated by prostaglandins and cyclic nucleotides. Cellular Immunology 1993; 149: 50–64.

18. Masferrer JL, Selbert K, Zweifel B, Needleman P. Endogenous glucocorticoids regulate an inducible cyclooxygenase enzyme. Proc Natl Acad Sci USA 1992; 89: 3917–3921.

Received 11 October 1995;
accepted 8 November 1995