The Inhibition of Neutrophil Granule Enzyme Secretion and Chemotaxis by Pertussis Toxin

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ABSTRACT Pertussis toxin treatment of rabbit peritoneal neutrophils causes a concentration-dependent inhibition of granule enzyme secretion induced by formylmethionyl-leucyl-phenylalanine, C5a, and leukotriene B4. It also inhibits chemotaxis induced by formylmethionyl-leucyl-phenylalanine. The same toxin treatment, however, has no effect on granule enzyme secretion induced by the calcium ionophore A23187 or phorbol 12-myristate 13-acetate. Moreover, pertussis toxin treatment does not affect either the number or affinity of the formylpeptide receptors on the neutrophil nor does it have any effect on the unstimulated levels of cyclic AMP (cAMP) or the transient rise in cAMP induced by chemotactic factor stimulation in these cells.

We hypothesize that pertussis toxin, as in other cells, interacts with a GTP binding regulatory protein identical with or analogous to either Ns or transducin which mediates the receptor-induced inhibition or activation of a target protein or proteins required in neutrophil activation. The nature of the target protein is unknown, but it is not the catalytic unit of adenylate cyclase. The target protein acts after binding of chemotactic factor to its receptor in the sequence that leads to the receptor-induced rise in intracellular Ca2+. It does not affect the responses elicited by the direct introduction of calcium into the cells or the activity of protein kinase C.

Two GTP binding regulatory proteins, Ns(Gs) and Nt(Gi), mediate the action of a number of hormones and other agents on adenylate cyclase. The proteins involved have been purified and studied in detail (1). Cholera toxin ADP-ribosylates and activates Nt (2). Pertussis toxin ADP-ribosylates and inactivates the inhibitory activity of Nt and the ability of transducin to mediate the light-induced activation of cyclic GMP (cGMP) phosphodiesterase in the retina (3, 4). Pertussis toxin has been crystallized (5, 6) and purified to homogeneity (4). Several observations suggest that GTP regulatory proteins may be involved in neutrophil activation. Nt has been demonstrated in neutrophils (7), and incubation of neutrophils with cholera toxin increases their levels of cyclic AMP (cAMP) and inhibits their chemotactic responsiveness (8, 9). It has been reported that nonhydrolyzable GTP analogues shift the affinity of the formylpeptide receptors of neutrophils (10), and that the chemotactic peptide N-formyl-norleucyl-leucyl-phenylalanine-leucyl-tyrosyl-lysine stimulates the GTPase activity of human neutrophil homogenates (11).

We therefore have tested the effect of pretreatment of rabbit peritoneal neutrophils with crystalline pertussis toxin on granule enzyme secretion and chemotaxis induced by the chemotactic factors, formylmethionyl-leucyl-phenylalanine (fMet-Leu-Phe), the fragment of the fifth component of complement (C5a), and the arachidonic acid metabolite, leukotriene B4 (LTB4), as well as on their stimulation by the calcium ionophore A23187 and phorbol 12-myristate 13-acetate (PMA). As we shall show, pretreatment with pertussis toxin inhibits chemotactic factor-induced chemotaxis and granule enzyme secretion from the neutrophil but has no detectable effect on enzyme release caused by PMA or A23187. No detectable effect of toxin treatment is evident on the binding

Abbreviations used in this paper: C5a, the fragment of the fifth component of complement; fMet-Leu-Phe, formylmethionyl-leucyl-phenylalanine; fNle-Leu-Phe, formylnorleucyl-leucyl-phenylalanine; LTB4, leukotriene B4, [SIS], 12(R)-dihydroxy-6,14-cis 8, 10 trans eicosatetraenoic acid]; Nt and Ns, two GTP binding regulatory proteins; PMA, phorbol 12-myristate-13 acetate.
of radiolabeled formylpeptides to their receptor or on the levels of neutrophil CAMP.

MATERIALS AND METHODS

Chemicals: The synthetic peptides Met-Leu-Phe and formylorleucyl-leucyl-phenylalanine (f-Ne-Leu-Phe, A23187, 2 x crystalline ovalbumin, p-nitrophenyl-N-acetyl-o-glucosaminide, and shellfish glycogen were obtained from Sigma Chemical Co. (St. Louis, MO). The radiolabeled peptides, Met-Leu-[\(^{3}H\)]Phe (48 Ci/mmol), f-Ne-Leu-[\(^{3}H\)]Phe (42 Ci/mmol), and [\(^{3}H\)]cAMP (37 Ci/mmol) were obtained from New England Nuclear (Boston, MA). CMC Cancer Research Chemicals was the source of the PMA, and LTB4 was a gift from Dr. P. Borgeat (Groupe de Recherches sur les Leucoцитes, Centre Hospitalier de l'Université Laval, Sainte-Foy, Quebec, Canada). Highly purified C5a was a generous gift from Dr. P. M. Henson (National Jewish Hospital and Research Center, Denver, CO). The crystalline pertussis toxin was purified and dissolved as described (5).

Rabbit peritoneal neutrophils obtained 4–12 h after the injection of 200–400 ml of sterile 0.1% shellfish glycogen were washed and treated as described (12). For granule enzyme secretion, neutrophils were suspended at a concentration of 5 x 10⁶ cells/ml in Mg²⁺-free modified Hanks' buffer with 1 mg/ml ovalbumin. They were incubated at 37°C with or without the indicated concentration of pertussis toxin; at the end of the indicated times, 0.94 ml of cell suspension was added to 50 μl cytochalasin B and 10 μl of the stimulating compound, and the mixture was incubated for 5 min more. For chemotaxis, 2.5 x 10⁴ cells/ml were incubated at 37°C for 1 h with or without toxin, and the chemotactic response was measured as indicated below.

Granule Enzyme Release: Granule enzyme release in the presence of 5 μg/ml of cytochalasin B was performed as previously described (12) and monitored by the assay of lysozyme and β-galactosaminidase. The lysozyme activity was determined by measuring the change in optical density of a suspension of Micrococcus lysodeikticus as described previously (12). β-Glucosaminidase was measured by the breakdown of its substrate p-nitrophenyl-N-acetyl β-glucosaminide as described (13), except that a modification by D. L. Kreutzer was followed in which a 300-μl aliquot was placed in a 96-well microtiter plate after the reaction was stopped, and the optical density was then determined at 410 nm with a Titertek Multiskan apparatus (Flow Laboratories, Inc., McLean, VA). The release of the two enzymes paralleled each other so that only the results for lysozyme are reported. The cells were also tested for lactic dehydrogenase leakage (12). Neutrophils pretreated with 10–1,000 ng/ml toxin for 45 min showed appreciable but submaximal inhibition of granule enzyme secretion (Fig. 1); at 60 min, the inhibition was indistinguishable from that obtained after a 90-min incubation (Fig. 1). As seen in Fig. 1, toxin treatment lowered the extent of release at every concentration of peptide tested. In the experiment pictured in Fig. 1, the inhibition was essentially complete in cells incubated with 200–1,000 ng/ml for 60 or 90 min. However, this varied somewhat among the four additional experiments performed; in some preparations of cells, inhibition was much more complete at 100 ng/ml than that shown in Fig. 1, whereas other cells were somewhat less sensitive to the action of the toxin. However, in all experiments, 200 ng/ml invariably gave maximal inhibition after a 60-min incubation. The results with β-galactosaminidase paralleled those with lysozyme, and there was no increase in lactic dehydrogenase leakage under any conditions of toxin treatment.

RESULTS

Inhibition by Pertussis Toxin of Granule Enzyme Secretion by Chemotactic Factors

The action of pertussis toxin shows a latent period. Incubation of rabbit neutrophils with 10–1,000 ng/ml pertussis toxin for 20 min at 37°C had no discernible effect on the ability of Met-Leu-Phe to induce secretion of lysozyme or β-glucosaminidase (results not shown), whereas cells incubated longer were distinctly inhibited. Neutrophils pretreated with 10–1,000 ng/ml toxin for 45 min showed appreciable but submaximal inhibition of granule enzyme secretion (Fig. 1); at 60 min, the inhibition was indistinguishable from that obtained after a 90-min incubation (Fig. 1). As seen in Fig. 1, toxin treatment lowered the extent of release at every concentration of peptide tested. In the experiment pictured in Fig. 1, the inhibition was essentially complete in cells incubated with 200–1,000 ng/ml for 60 or 90 min. However, this varied somewhat among the four additional experiments performed; in some preparations of cells, inhibition was much more complete at 100 ng/ml than that shown in Fig. 1, whereas other cells were somewhat less sensitive to the action of the toxin. However, in all experiments, 200 ng/ml invariably gave maximal inhibition after a 60-min incubation. The results with β-glucosaminidase paralleled those with lysozyme, and there was no increase in lactic dehydrogenase leakage under any conditions of toxin treatment.

As is evident from Fig. 2, pretreatment of neutrophils at 37°C for 60 min with 500 ng/ml toxin caused complete inhibition of granule enzyme secretion induced by C5a or LTβ. Despite appearances (Fig. 2), when the corresponding curves were analyzed as described for the binding studies, the lower concentrations of LTβ, and C5a showed no significant differences in their ability to release enzyme from toxin-treated and untreated cells. The same pattern as in Fig. 2 was seen in one additional experiment.
Toxin Effect on Enzyme Release by PMA and A23187

As Fig. 3 demonstrates, incubation of rabbit neutrophils with 500 ng/ml toxin for 60 min at 37°C had no effect on lysozyme release induced by PMA. In the same experiment, toxin treatment completely abolished the secretagogue activity of fMet-Leu-Phe plus cytochalasin B. Chemotactic factors require cytochalasin B to release specific and azurophil granule contents from neutrophils in suspension, and cytochalasin B enhances release by A23187 (18). PMA does not require cytochalasin B to induce release of specific granule constituents but does need it to induce the secretion of azurophil granule enzymes (19). In the experiment pictured in Fig. 3 and in an additional experiment, cytochalasin B was not added to the PMA. In two other experiments not shown here, there was no inhibition of lysozyme or β-glucosaminidase secretion from toxin-treated neutrophils in the presence of 5 μg/ml cytochalasin B and PMA. Thus, neither the presence nor absence of cytochalasin B affects the inability of pertussis toxin to inhibit enzyme release by PMA.

The calcium ionophore A23187 also induces granule enzyme secretion from rabbit neutrophils (18). Incubation of rabbit neutrophils with 500 ng/ml toxin for 60 min at 37°C had no reproducible effect on either lysozyme release induced by A23187 (Fig. 4) or on glucosaminidase secretion (not shown). When the two curves of Fig. 2 were analyzed for equivalence essentially as described for the binding studies, the ED₅₀ for the toxin-treated cells was 0.83 × 10⁻⁶ M, whereas that for the untreated control was 1.2 × 10⁻⁶ M, a small but statistically significant difference (P < 0.02). However, a second experiment done the same way did not confirm this result—the ED₅₀ for the toxin-treated neutrophils was 4 × 10⁻⁷ M, and that for the untreated control was 2.6 × 10⁻⁷ (P > 0.1).

Toxin Inhibition of Chemotaxis

Fig. 5 shows that the pretreatment of neutrophils with the toxin also inhibited their chemotactic responsiveness to fMet-Leu-Phe.
Leu-Phe. The sensitivity of the chemotactic reactivity to toxin treatment was at least as great as that of the granule enzyme secretory response and may be somewhat greater. The same results were seen in a duplicate experiment. Interestingly, there appeared to be no effect of toxin treatment on the penetration of the filter by the cells in the unstimulated buffer control.

Effect of Pertussis Toxin on Formyl Peptide Binding

Three studies of fNle-Leu-[3H]Phe–specific binding were performed to assess the effect of the pretreatment of rabbit neutrophils with 500 ng/ml pertussis toxin at 37°C for 60 min. Scatchard plots of formyl peptide binding in one typical study are shown in Fig. 6. The Scatchard plots were invariably curved for both control and toxin-treated cells. Analysis by the LIGAND computer program indicated that the data were consistent with the binding of fNle-Leu-[3H]Phe to two independent sets of binding sites: the equilibrium dissociation constants (Kd) for these sites averaged 1.0 x 10^-9 and 1.2 x 10^-8 M and 8% of the sites, on average, were of the higher affinity. In the study illustrated (Fig. 6), the fit to the complete experimental data for both control and toxin-treated cells was not significantly worsened (F = 1.29 with 4 and 20 degrees of freedom; P > 0.2) under the constraints that the binding capacities and affinities were unaffected by toxin treatment. Moreover, the experimental data points for both control and toxin-treated cells all lay within the 95% confidence limits around the constrained composite curve. Data from the other two studies with fNle-Leu-[3H]Phe showed the same pattern. Toxin treatment again did not significantly affect the binding of formyl peptide to either binding site (F = 0.19 and 0.76; P > 0.5 in each case).

Four studies were performed with fMet-Leu-[3H]Phe (data not shown). The curvature of the Scatchard plots was less definitive with this formyl peptide, and the Kd values for the two sites (6.8 x 10^-10 and 4.1 x 10^-9 M) were lower than with fNle-Leu-[3H]Phe. In two of the studies, toxin treatment had no significant effect on the binding of this formyl peptide (F = 2.60 and 0.97; P > 0.05 and P > 0.5, respectively); in the third and fourth, however, a small increase in one and decrease in the other in the overall binding capacity appeared to occur after toxin treatment.

Effect of Pertussis Toxin on the Basal and fMet-Leu-Phe–stimulated Levels of cAMP

We also examined the effect of pretreatment of rabbit neutrophils with toxin on the basal and fMet-Leu-Phe–stimulated rise in intracellular level of cAMP. The results summarized in Table I clearly show that the addition of toxin does not significantly affect the basal or the stimulated cAMP level.

DISCUSSION

The ability of pertussis toxin under the appropriate conditions to completely inhibit chemotaxis and granule enzyme secretion induced by the chemotactic factors, fMet-Leu-Phe, C5a, and LTB4, is strong evidence for the presence of a guanine nucleotide binding regulatory protein in the neutrophil identical with or analogous to N1 or to transducin. In an abstract that appeared as this work was being prepared for publication, Goldman et al. (20) reached a similar conclusion when they...
also found that pertussis toxin inhibits the activation of human neutrophils by chemotactic factors. More direct evidence for this conclusion are the unpublished findings of F. Okajima and M. Ui (referred to in reference 21) and C. K. Huang of this institution, that pertussis toxin induces ADP-ribosylation of a 41-kD membrane protein from guinea pig and rabbit neutrophils, respectively. The inhibition of neutrophil activity by pertussis toxin is also strong evidence that the process or processes that this N protein regulates plays a necessary role in neutrophil function. The inhibition of both enzyme secretion and chemotaxis by pertussis toxin is concentration dependent and, most tellingly, its action requires a latent period. Presumably, as in all other cells where it has been tested, the latent period is required for the pertussis toxin to bind to the cell and be internalized to exert its function. The neutrophil possesses a protein identical with or similar to Ns (7). Cholera toxin which acts through Ns to raise cAMP levels inhibits stimulated neutrophil function (8, 9). However, no matter what concentration of toxin or time of preincubation is used, the inhibition is never more than 40–50%. This suggests that unlike the process regulated by the N protein susceptible to pertussis toxin, the neutrophil process or processes affected by Ns may not be absolutely required for cell function or that there are pathways involved in the cell functions that are independent of the latter.

One possible mechanism of the inhibition is that the toxin treatment affects chemotactic receptor binding. Pertussis toxin treatment decreases the affinity of the D2 receptor for dopamine (22) and the \( \alpha_2 \)-adrenergic, the cholinergic, and opiate receptors for their respective ligands (23). Garcia-Saenz et al. (24) have reported that pertussis toxin treatment induces a decreased formation of the high-affinity state for \( \alpha_2 \)-adrenergic agonists. Neutrophils contain high- and low-affinity receptors for the formylpeptides (25, 26), and guanine nucleotides have been reported to transform the high-affinity state of the formylpeptide receptor of neutrophils and macrophages into a lower affinity state (10). However, pertussis toxin treatment of neutrophils sufficient to completely inhibit the secretagogue action of fMet-Leu-Phe has no detectable effect on either the affinity or number of high- or low-affinity formylpeptide binding sites. This indicates that toxin treatment does not act on receptor binding but at some process or processes after receptor-chemotactic factor interaction. It is unknown whether the lack of effect of toxin treatment on receptor binding is because the putative N protein does not mediate changes in receptor affinity or whether, with the experimental conditions used, guanine nucleotide regulation of the binding site is nonexistent or not prominent.

In many cells, Ns is coupled to adenylate cyclase, and in these cells, treatment with pertussis toxin prevents the inhibition of adenylate cyclase which results from receptor-agonist interaction (3, 4). This does not appear to be true of chemotactic factor-receptor interaction in neutrophils. Treatment of neutrophils with toxin under conditions that completely inhibit the ability of fMet-Leu-Phe to induce granule enzyme secretion has no significant effect on the level of cAMP in the same cells. fMet-Leu-Phe induces a rapid, transient increase in neutrophil intracellular cAMP (17, 27) which, however, is not required for the activation involved in granule secretion or the generation of O2− (28). Toxin treatment of the neutrophils causes no change in the transient rise induced by fMet-Leu-Phe. Although it is not known whether the receptor-mediated rise of cAMP occurs through the activation of adenylate cyclase, this finding does emphasize that the effect of pertussis toxin is not mediated through an increase of cAMP. This is again in contrast to the action of chola toxin, in which the inhibitory action has been associated with such a rise (8, 9). Nakamura and Ui (29) have reported that cAMP does not appear to play a role in the inhibition of stimulated histamine release in rat mast cells treated with pertussis toxin. These findings suggest that in both the mast cell and in the neutrophil, the N protein acted upon by pertussis toxin may not be coupled to adenylate cyclase.

Our ignorance as to the nature of the putative GTP-binding regulatory protein that is the presumed target of the pertussis toxin extends to the general nature of the process that is inhibited. There are at present two possibilities. The first is that the toxin, in reacting with its presumed neutrophil N protein, interferes with the inhibition by that activated N protein of some receptor-mediated process; this would be analogous to the manner in which the toxin in other cells interacts with Ns to prevent its inhibition of adenylate cyclase. The second possibility is that the toxin, in interacting with N protein, prevents its activation of some necessary process; the analogy here is the way pertussis toxin prevents retinal transducin from activating the cGMP phosphodiesterase (1).

This work, although throwing no light on the function of the target of toxin action other than providing some examples of what it is not, clearly pinpoints the area in the process of neutrophil activation where this function is exerted. At present, most investigators believe that chemotactic factors such as fMet-Leu-Phe, C5a, LTB, etc., activate neutrophils through, among other things, the combined action of a rise in cytosolic Ca2+ with its resultant reactions, and the activation of protein kinase C and the reactions that ensue from this. The lack of effect of pertussis toxin on the granule enzyme release induced by PMA indicates that the action of pertussis toxin does not involve the sequence of reactions initiated by the activation of protein kinase C.

Treatment of the cell with toxin also does not affect granule enzyme release initiated by the influx of Ca2+ caused by the Ca2+ ionophore, A23187. This is consistent with the conclusion that the final locus of toxin action is at one or more of the reactions that occur between chemotactic receptor stimulation and the resultant rise in intracellular Ca2+. This conclusion is also fully supported by our recent finding that the rise in intracellular Ca2+ induced by fMet-Leu-Phe or LTB, is greatly reduced or abolished in pertussis toxin–treated neutrophils (30). Which reaction or reactions is the ultimate

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**Table I**

*Effect of Pretreatment with Pertussis Toxin on the Basal and fMet-Leu-Phe–stimulated cAMP in Rabbit Neutrophils*

| Time (min) | Basal (pmol/10^9 cells) | fMet-Leu-Phe (pmol/10^9 cells) |
|-----------|-------------------------|-----------------------------|
| Control cells | 6.9 ± 0.4 | 9.5 ± 0.3 |
| 30         | 6.4 ± 0.25 | 10.5 ± 0.25 |
| 60         | 7.0 ± 0.3 | 9.0 ± 0.15 |
| Toxin-treated cells (500 ng/ml) | 6.1 ± 0.2 | 9.0 ± 0.2 |
| 30         | 6.3 ± 0.3 | 9.9 ± 0.3 |
| 60         | 6.5 ± 0.25 | 9.5 ± 0.25 |

Time is in minutes at 37°C with or without the addition of the toxin. The cells were treated with 10−8 M fMet-Leu-Phe for 1 min before the reaction was started. The values represent the mean ± SEM of at least three determinations.
target of toxin action in the sequence that precedes the rise in intracellular Ca\(^{2+}\) is presently under study. In the course of this study, we have recently found (31) that the addition of pertussis toxin to rabbit neutrophils inhibits the fMet-Leu-Phe-induced rises in Na\(^{+}\) influx, intracellular pH, and the stimulated changes in polyphosphoinositides and the phosphorylation of a 46-kD protein. Unlike the effect of fMet-Leu-Phe, the increases in Na\(^{+}\) influx and intracellular pH produced by PMA are not inhibited by the toxin. Also in accordance with the present results is the recent observation that exposure of guinea pig neutrophils to pertussis toxin results in a marked inhibition of the arachidonic acid release from these cells that occurs after chemotactic factor stimulation (referred to in references 21 and 32; see also references 32 and 33). After this manuscript was submitted, Okajima and Uli (32) and Bokoch and Gilman (33) published conclusions similar to those researched here.

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