Demonstration of Reversible Priming of Human Neutrophils Using Platelet-Activating Factor

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Exposure of neutrophils to agents such as lipopolysaccharide, tumor necrosis factor-α (TNF-α), and the granulocyte-macrophage colony-stimulating factor causes a major upregulation of subsequent agonist-induced NADPH oxidase activation. This priming effect is a prerequisite for neutrophil-mediated tissue damage and has been widely considered to be an irreversible process. We have investigated the potential for neutrophils to recover from a priming stimulus by studying the effects of platelet-activating factor (PAF). PAF did not stimulate respiratory burst activity directly, but caused a rapid (maximal at 10 minutes) and concentration-dependent (EC₅₀ 50.2 nmol/L) increase in N-formyl-methionyl-leucyl-phenylalanine (fMLP)-stimulated superoxide anion release. At time-points >10 minutes, this priming effect spontaneously declined, with recovery to basal levels of fMLP-stimulated superoxide anion generation by 120 minutes. An identical priming time-course was observed with N-methyl carbamyl PAF, a non-metabolizable analogue of PAF, indicating that the transient nature of PAF-induced priming was not secondary to PAF metabolism. Two structurally diverse PAF receptor antagonists (UK-74,505 and WEB 2066), added 10 minutes after PAF addition, increased the rate of decay of the priming effect. In contrast, TNF-α–induced priming, which was of a similar magnitude to that observed for PAF, was slower to evolve (maximal at 30 minutes) and remained constant for at least 120 minutes. The reversible nature of PAF-induced priming was confirmed by demonstrating that PAF–, but not TNF-α–, induced cell polarization (shape change) and CD11b-dependent neutrophil binding of albumin-coated latex beads was also transient, with return to basal, unstimulated levels by 120 minutes. Furthermore, cells that had spontaneously deprimed following PAF exposure retained their capacity to be fully reprimed by a subsequent addition of either PAF or TNF-α. These data imply that neutrophil priming is not an irreversible event: the demonstration of a cycle of complete priming, depriming, and repriming offers the potential for functional recycling of neutrophils at sites of inflammation.

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Neutrophils play a fundamental role in the acute inflammatory response, destroying invading microbial pathogens and thereby minimizing infection of the host. The response of neutrophils to various proinflammatory stimuli is largely determined by their previous exposure to agents such as cytokines (eg, tumor necrosis factor-α [TNF-α], and interleukin-8, [IL-8]), lipid mediators (eg, platelet-activating factor [PAF] and leukotriene B₄ [LTB₄]) or bacterial products (eg, N-formylmethionyl-leucyl-phenylalanine [fMLP], and lipopolysaccharide [LPS]). At physiologically relevant concentrations these agonists elicit cell polarization, recruitment, and activation of cell-surface β₃-integrins (eg, CD11b/CD18), and enhance, or ‘prim,’ neutrophil responses (eg, phagocytosis, respiratory burst activation, degranulation) to other secretagogue agonists. In vivo data suggest that priming also plays a critical role in the recruitment of neutrophils to an inflamed site. However, although this switching of neutrophils from a relatively unresponsive to a hyperresponsive state is a prerequisite for physiological neutrophil-mediated bacterial destruction, it may, if uncontrolled, lead to neutrophil-mediated tissue damage.

Previous studies have demonstrated that human peripheral blood neutrophils, incubated with the priming agents granulocyte colony-stimulating factor G-CSF or LPS, maintain an enhanced superoxide anion secretory response to fMLP for at least 24 hours. Studies undertaken in vivo have demonstrated that sheep peripheral blood and bone marrow-derived neutrophils also remain primed for at least 24 hours following endotoxin LPS infusion, suggesting that maintenance of the primed state is an important part of the long-term inflammatory response to endotoxin. These observations have been widely interpreted as indicating that neutrophil priming is an essentially irreversible phenomenon.

Despite its obvious importance to the regulation of inflammation, little attention has been given to the potential for neutrophils, once primed, to revert to their former quiescent state, ie, to be “deprimed.” However, in two studies where neutrophil priming has been induced using physicochemical stimuli ie, hypotonic treatment, or exposure to the highly-charged Ca²⁺-chelator, inositol hexakisphosphate, priming of the superoxide anion response appeared to be transient. The lack of study in this area may, at least in part, reflect the difficulties encountered in isolating and maintaining these cells in an unprimed state ex-vivo, or ensuring complete removal or antagonism of the initial priming signal. In addition, isolated neutrophils have a relatively short life-span due to their high rate of constitutive programmed cell death or apoptosis. For these reasons, most in vitro studies have focused on the short-term effects of priming agents and the cellular mechanisms responsible for such events.

In view of the potential pathophysiological, and hence therapeutic, importance of being able to rescue neutrophils from the primed state, we have investigated the possible reversibility of neutrophil priming induced by physiological, receptor-mediated priming agents. Using human peripheral blood neutrophils incubated at a concentration of PAF that causes a rapid enhancement of fMLP-stimulated respiratory burst activity without any direct effect on superoxide anion release, we observed a spontaneous and complete decay of

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the PAF-primed superoxide anion response and PAF-induced CD11b/CD18 activation and to a lesser extent, PAF-induced shape change. The rate of neutrophil recovery following PAF addition could be enhanced by the use of selective PAF receptor antagonists (WEB 2086 and UK-74,505). Furthermore, the deprived cells retained their full capacity to be reprimed by an alternative priming agent (TNF-α) or a further addition of PAF. The ability of neutrophils to participate in a complete priming/depriming/repriming cycle allows for greater flexibility in the control of neutrophil behavior at an inflammatory site than was hitherto realized.

**MATERIALS AND METHODS**

**Neutrophil preparation.** Peripheral venous blood was taken from healthy adult volunteers, anticoagulated with 4 mL 3.8% sodium citrate/40 mL blood, and centrifuged (300g) for 20 minutes. Neutrophils were isolated exactly as previously detailed using dextran sedimentation and discontinuous Percoll gradients. This isolation technique yields neutrophils that display very low levels of basal shape change (<8% assessed flow-cytometrically) or direct fMLP-induced superoxide anion generation. The purified neutrophils were washed sequentially in platelet-poor plasma, phosphate-buffered saline (PBS) without, and PBS with, CaCl₂ and MgCl₂. Cell purity and viability (trypan blue exclusion) were routinely >95% (<0.5% monocye contamination) and >99.5%, respectively.

**Shape change assay.** Neutrophils (10⁶ in 90 µL PBS containing CaCl₂ and MgCl₂) were equilibrated in a gently shaking water-bath for 5 minutes at 37°C. Priming agents were added in a 10-µL volume to achieve the required drug concentrations (PAF 1 nmol/L to 10 µmol/L, TNF-α 200 U/mL) and incubations continued for the periods stated. Preliminary experiments demonstrated this concentration of TNF-α to be optimal in causing maximal enhancement of fMLP-induced superoxide anion generation with minimal direct respiratory burst activation (data not shown). To determine the IC₅₀ values of the PAF receptor antagonists used, neutrophils were incubated with WEB 2086 or UK-74,505 (both at 10 nmol/L to 10 µmol/L) for 30 minutes before the addition of priming agents. For investigations examining the reversibility of PAF-induced priming, neutrophils were treated with PAF (1 µmol/L) for 10 minutes before addition of 1 µmol/L WEB 2086 or UK-74,505. fMLP (100 nmol/L) or buffer (PBS) was added to samples (final volume 1 mL) 10 minutes before the addition of an equal volume of 2.5% glutaraldehyde. Samples were analyzed for shape change by flow cytometry (Coulter EPICS Profile II, Coulter Electronics, Luton, UK) using a slight modification of a previously published method. Percentage shape change was calculated from the mean forward light scatter of each sample by gating on the non-shape changed neutrophil population. The values obtained using this method correlate closely with those derived by direct visual assessment of shape change, with the exception that the flow cytometric method of assessment slightly overestimates the extent of basal shape change.

**Superoxide anion release assay.** Neutrophils were isolated, equilibrated at 37°C, and incubated with PAF or PBS exactly as detailed above, except that cytochrome C (800 µL, 1 mg/mL) was added immediately before the addition of fMLP. One of each set of quadruplicate determinations included superoxide dismutase (375 U) to allow confirmation of the specificity of cytochrome C reduction. Reactions were stopped by placing the cells on ice, followed by centrifugation (1,500g for 2 minutes, 4°C). The superoxide dismutase-inhibitable reduction of cytochrome C was determined in each supernatant by measuring the peak absorbance between 553 and 565 nm using a Pye-Unicam scanning spectrophotometer, and expressed as nanomoles superoxide anions generated per 10⁶ neutrophils. In experiments designed to assess the ability of PAF-recovered neutrophils to be reprimed with either TNF-α or a further addition of PAF, cells were treated with PAF (1 µmol/L) or PBS for 120 minutes, before a final incubation with PAF (1 µmol/L, 10 minutes) or TNF-α (200 U/mL, 30 minutes) and assessment of fMLP-stimulated superoxide anion release.

To examine the effects of hypotonic challenge on neutrophil function, cells (10¹⁰ in 250 µL PBS) were equilibrated at 37°C as outlined above and incubated for 19 minutes in PBS containing 80 µmol/L cytochrome C, with 150 mmol/L NaCl (isotonic incubations) or 50 mmol/L NaCl (hypotonic incubations). Neutrophils were then treated for 1 minute with 20 µL of either 5 mol/L NaCl (to reverse hypotonicity to isotonicity) or PBS (to retain hypotonicity or isotonicity). The effects of the hypotonic challenge itself on basal and fMLP-stimulated superoxide anion generation, together with the ability of these cells to deprime following restoration of isotonicity and thereafter be reprimed with PAF, was then assessed as detailed above.

**Neutrophil adhesion to albumin-coated latex beads (ACLB).** Fluorescent latex beads (2.5% packed vol/vol stock solution as purchased) were washed (three times) in PBS, resuspended at 2.5% (vol/vol) in PBS containing 10 mg/mL human serum albumin, and incubated for 19 minutes at 25°C. The resultant ACLA were again washed (three times) in PBS and finally resuspended at 0.75% (vol/vol). Neutrophils (175 µL aliquots at 10⁶/mL, in PBS with CaCl₂ and MgCl₂) were incubated in a shaking water-bath at 37°C for 5 minutes, and then treated with PAF (1 µmol/L), TNF-α (200 U/mL) or PBS (all added in a 15-µL volume) for 0 to 120 minutes. ACLA (25 µL of 0.75% vol/vol solution) were added to each tube 15 minutes before the termination of each reaction, except for time points <15 minutes where the beads were added before the agonist. Neutrophils were then fixed by the addition of 0.5 mL of 0.5% glutaraldehyde. After 30 minutes at room temperature, sonicated ACLA were removed by washing with PBS (three times) and bead-binding to the neutrophils assessed using an EPICS Profile II (Coulter Electronics), as previously detailed.

**Statistics.** All values are expressed as means ± standard error of mean (SEM) of (n) number of separate experiments. Values, where applicable, were compared by ANOVA or the Student's t-test for paired data, with P < 0.05 considered to be significant. Significant differences between groups were determined by the Newman-Keuls procedure.

**Materials.** fMLP, PAF, superoxide dismutase (SOD), cytochrome C, PBS (with or without CaCl₂ and MgCl₂), dextran-500, Percoll, human serum albumin and glutaraldehyde (25%) were purchased from Sigma (Poole, UK). TNF-α was obtained from Genzyme (Cambridge, MA). One micron fluorescent microspheres were purchased as a 2.5% solids-latex (2.5% vol/vol) stock solution from Polysciences Inc through the UK supplier Park Scientific (Nottingham, UK). WEB 2086 and UK-74,505 were gifts from Boehringer Ingelheim Ltd (Berks, UK) and Dr J. Parry (Pfizer, Sandwich, UK), respectively. 1-O-alkyl-2-N-methylcarbamyl-glycerophosphocholine (N-methyl carbamyl PAF) was obtained from Calbiochem (Nottingham, UK).

**RESULTS**

PAF is an established and important inflammatory mediator in vivo. It was selected for this study because its priming effect in neutrophils is rapid, receptor-mediated, associated with minimal direct activation of superoxide anion release, and inhibitable by specific, high-affinity PAF receptor antagonists. Under our own experimental conditions, PAF (1 nmol/L to 10 µmol/L) did not affect spontaneous superoxide anion release (Fig 1A), but caused a rapid (maximal at 10 minutes), concentration-dependent increase in fMLP-stimulated superoxide anion release (EC₅₀, 50.2 nmol/
KITCHEN ET AL

L, Fig 1A), and a similar concentration-dependent increase in shape change (EC₅₀ 110 nmol/L, Fig 1B). In the shape change experiments, 10 μmol/L PAF appeared to have less effect than 1 μmol/L PAF, but this correlated with the light-microscopic observation of large, round, “glassy”-looking cells, suggestive of cell swelling. In view of these findings, a PAF concentration of 1 μmol/L was chosen for all further priming studies.

PAF-induced priming of superoxide anion generation in neutrophils is reversible. Figure 2 illustrates how the length of the initial PAF incubation period affects the subsequent enhancement of superoxide anion release in response to fMLP. The ability of PAF to prime the fMLP-response was maximal after a 10-minute PAF preincubation, with the priming effect decaying thereafter, to approach unprimed levels by 2 hours (Fig 2). Notably, the pattern of reversal of the PAF priming effect was consistently biphasic, with an initial rapid loss in priming occurring within 15 to 30 minutes of PAF addition, followed by a second, slower phase of decay. This progressive decline in the magnitude of the primed fMLP-superoxide anion response was not due to cell necrosis, as viability (assessed by trypan blue exclusion) was routinely >95% for all time points studied.
In an attempt to elucidate some of the possible factors responsible for this time-dependent reversal of PAF-mediated neutrophil priming, additional experiments were undertaken to assess the role of PAF metabolism and PAF receptor desensitization. Firstly, PAF was substituted by a nonmetabolizable analogue, N-methyl carbamyl PAF. This resulted in a near identical time course (data not shown) to that illustrated in Fig 2, indicating that PAF degradation was not responsible for the loss in the priming effect. Secondly, we examined the ability of two specific, but structurally different, PAF receptor antagonists, WEB 2086 and UK-74,505, to influence the rate of depriming. Preliminary studies established optimal conditions for the use of these antagonists: a 30-minute preincubation with UK-74,505 caused a concentration-dependent (IC \textsubscript{50} 68 nmol/L) and complete (at 1 \mu mol/L) inhibition of the PAF-primed superoxide anion response, whereas inhibition by WEB 2086 was biphasic and incomplete (55% ± 4% inhibition with 10 \mu mol/L WEB 2086, data not shown). Neither of these compounds, at the concentrations used, affected neutrophil viability nor superoxide anion release in control or fMLP-treated cells (data not shown). Thus, to investigate the influence of PAF receptor blockade on the rate of decay of PAF-induced priming, both antagonists were used at a concentration of 1 \mu mol/L. When WEB 2086 (1 \mu mol/L) or UK-74,505 (1 \mu mol/L) was added 10 minutes after PAF, a small but significantly faster (P < 0.05) rate of decay of the PAF-primed superoxide anion response was observed (Fig 2), with UK-74,505 having the greater effect. This data suggests that although PAF receptor desensitization or uncoupling may play a role in the decay of the priming effect, this process is not complete following a 10-minute incubation with 1 \mu mol/L PAF.

In marked contrast to the priming time course observed with PAF, TNF-α-induced priming, although slower to evolve (maximal at 30 minutes), remained constant for at least 2 hours (nanomoles superoxide anion released: at 30 minutes: fMLP (100 nmol/L) 4.6 ± 1.6, TNF-α (200 U/mL) + fMLP 20.1 ± 3.2; at 2 hours: fMLP 5.0 ± 0.7, TNF-α + fMLP 19.2 ± 4.9, n = 3).

**Transient effects of PAF on neutrophil shape change and AChE binding.** To validate our observations of neutrophil recovery following PAF-mediated priming of the respiratory burst, we undertook further time course studies to examine the effects of PAF on neutrophil shape change and CD11b activation. Shape change was chosen because previous studies have demonstrated a tight correlation between priming of the superoxide anion response and the extent or proportion of neutrophils that have undergone cell polarization. In addition, the relatively weak priming effect of IL-8 on superoxide anion generation has been reported to partially reverse with time without any concomitant recovery of CD11b expression.

Incubation of neutrophils with 1 \mu mol/L PAF caused a rapid (maximal at 2 minutes) increase in shape change, which then declined spontaneously towards basal levels by 30 minutes (Fig 3). The subsequent small increase in percent shape change, observed between 30 to 120 minutes, paralleled the changes seen in control cells. The extent of the initial shape change response to PAF was similar to that observed following a 10-minute incubation with 100 nmol/L fMLP (80.8% ± 7.1%, n = 3). It should be noted here that flow-cytometric quantification
of shape change, although a convenient and highly reproducible assay, gives consistently higher levels of basal shape change (approximately 8%\(^1\)) than those obtained by direct visual assessment of cell morphology. Our data confirm, however, that PAF-induced shape change, like priming of the superoxide anion response, is a transient event. Neutrophil shape change to TNF-\(\alpha\) (200 U/mL) was of a similar magnitude (70.1\% ± 1.8%, n = 4) to that induced by PAF, but was slower to evolve (plateau at 30 minutes) and remained constant for the 2-hour incubation period (Fig 3).

As a third index of priming, we followed the \(\beta_2\)-integrin-dependent binding of ACLB over a 2-hour incubation with either PAF or TNF-\(\alpha\). Again, PAF (1 \(\mu\)mol/L) induced a time-dependent increase in ACLB binding, maximal after 10 minutes, which declined to reach control levels by 2 hours (Fig 4). TNF-\(\alpha\) (200 U/mL) also augmented ACLB binding but, unlike PAF, the extent of bead binding reached a plateau at 30 minutes and remained constant for the ensuing 90-minute incubation period (Fig 4).

Repriming of neutrophils with PAF or TNF-\(\alpha\). We next investigated whether neutrophils that had primed and then spontaneously deprimed during a 120-minute incubation with PAF were capable of being reprimed. Figure 5 demonstrates that PAF-recovered neutrophils retain their full capacity to be reprimed when challenged again with either PAF (1 \(\mu\)mol/L, 10 minutes) or TNF-\(\alpha\) (200 U/mL, 30 minutes), generating similar amounts of superoxide anions upon fMLP stimulation as freshly-primed cells. This finding was repeated when neutrophils were primed and deprimed using a modification of a previously described hypotonic challenge protocol.\(^2\) Under isotonic conditions, fMLP (100 nmol/L) and PAF (1 \(\mu\)mol/L) alone elicited little superoxide anion release, with PAF enhancing the fMLP-stimulated superoxide anion response by 3.8-fold (Table 1). A 20-minute hypotonic challenge resulted in a modest (twofold) priming of the fMLP response, which recovered towards control levels when isotonicity was restored for 1 minute. Subsequent treatment with PAF reprimed the fMLP response, which recovered towards control levels when isotonicity was restored for 1 minute. Subsequent treatment with PAF reprimed the fMLP response, albeit to a slightly lower level than that observed in cells maintained under isotonic conditions. Cell viability was routinely >95% for all conditions studied. Thus, like cells that had deprimed following PAF exposure, osmotically primed and deprimed neutrophils also retained their capacity to be primed for a second time by a physiological agonist such as PAF.

DISCUSSION

The neutrophil can exist in a number of different functional states and this has a significant bearing on its behavior.
and responsiveness in vitro. Thus, in the unprimed state, the neutrophil displays little or no secretory response when incubated with an agent such as fMLP, whereas such a challenge in a fully primed cell results in an explosive increase in respiratory burst activity; this priming-activation axis has been shown to be a major determinant of neutrophil behavior in vivo. However, the very protracted priming effect of agents such as LPS, G-CSF, and GM-CSF, together with the short life-span of the neutrophil, has led to the belief that priming is a largely irreversible process. Indeed, the sustained nature of the priming effect has been postulated to play a fundamental role in the long-term inflammatory response observed with certain agents, including endotoxin.

In this report, we provide evidence that neutrophil priming is not an irreversible process and, moreover, that these cells, once deprimed, can go through a further complete cycle of priming and activation.

The depriming of neutrophils observed following PAF treatment was apparent for fMLP-stimulated superoxide anion generation, CD11b function, and cell polarization, and hence was unlikely to represent selective downregulation of one particular component of the priming response, as reported with IL-8. The ability of neutrophils to be reprimed by TNF-α and PAF after a 2-hour incubation, with maintenance of full viability throughout, excludes the possibility that the loss of the PAF priming effect was merely a consequence of the extended incubation procedure affecting cell integrity or metabolic status. While the basis for the decline in PAF-mediated priming is uncertain, the identical nature integrity or metabolic status. While the basis for the decline in PAF-mediated priming is uncertain, the identical nature of the time-course of priming of superoxide anion release with N-methyl carbamyl PAF, a biologically active PAF analog that is completely resistant to metabolic inactivation by neutrophils or human serum, makes PAF metabolism unlikely. We have also shown that inclusion of adenosine deaminase in these incubations does not influence the time-
course of PAF-primed superoxide anion responses, which excludes a secondary effect mediated via adenosine release and autocrine activation of cyclic adenosine monophosphate (AMP)-dependent protein kinase pathways (Kitchen, Rossi and Chilvers, unpublished observations, February 1995). Although homologous receptor desensitization may underlie the transient nature of the PAF signal, the increased rate of decay of fMLP-induced superoxide anion release following UK-74,505 or WEB 2086 addition and the return of a fully competent PAF priming response after 2 hours suggests that PAF receptor uncoupling/desensitization is both incomplete and transient. These data are consistent with previous studies demonstrating rapid activation-induced uncoupling and internalization of PAF receptors followed by subsequent receptor re-expression. The recovery of PAF receptor number and function is likely to reflect extensive membrane attachment and metabolism of PAF (approximately 1 pmol/10^7 neutrophils/min).24,25

From our own comparisons of PAF and TNF-α and other published observations, it would appear that neutrophil priming in vitro falls into three categories: (1) fully reversible (eg, that induced by PAF, osmotically swelling, or osmotic hexakisphosphate); (2) partially reversible (eg, with IL-1 or IL-8); or (3) largely irreversible (eg, with GM-CSF, G-CSF, or LPS). Further studies would be required to categorize TNF-α because its effects did not show any signs of recovery over the 2-hour incubation period used in this study, but have been reported to decay over 24 hours. It is also intriguing to note that only agents in group (3) are able to modulate the rate of neutrophil apoptosis, which again testifies to the long duration of action of this class of agents. While it is clear that neither the efficacy nor extent of the initial priming signal dictates the reversibility of the primed state (because PAF, TNF-α, LPS, and GM-CSF [data not shown] induce equivalent levels of priming), it is possible that the duration of the priming signal and/or its rate of onset are key determinants. However, in the absence of any clear mechanistic basis for neutrophil priming, it is also possible that the above agents use discrete signalling pathways to induce their priming effects.

This current observation of reversible priming may allow the pro-inflammatory, and potentially tissue-damaging, effects of neutrophil priming/activation to be counteracted by a process other than apoptosis or the pharmacological inhibition of neutrophil activation. It is unlikely that neutrophils within an inflammatory focus would be exposed in isolation to PAF or other “transient” priming agents. However, as endothelial cell-associated PAF has been shown to play a central role in neutrophil priming and migration through IL-1β–treated human umbilical vein endothelial cell monolayers in vitro,27 and endogenously formed PAF is involved in leukocyte extravasation induced by IL-1 in vivo,28 any delay in cell exit through an activated endothelial surface may permit cell recovery and the return of unprimed neutrophils to the circulation. Thus, the recognition that neutrophils have the potential to deprime allows an additional point of control in the early stages of the acute inflammatory response, whereby cells may retain to their former quiescent state and potentially re-enter the circulating neutrophil pool. These deprimed neutrophils, once fully recovered, could again attain their maximal priming potential and mount subsequent responses, as dictated by ensuing inflammatory challenges. In contrast, priming agents with a longer duration of action would maintain neutrophils in the primed state for a much longer period of time and may, therefore, play a distinct role in vivo, in the wake of a more widespread or prolonged inflammatory insult.

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